Radiata: An Economic Breeding Objective

The definition of an economic breeding objective for plantation radiata pine grown to produce timber flitch and newsprint and an investigation of some aspects related to short-rotation breeding in general using plantation eucalypts as an example.

by

Paul Chambers

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Authority of Access

Declarations

This thesis does not contain any material which has been accepted for a degree or diploma by the University of Tasmania or any other institution. To the best of my knowledge and belief this thesis contains no material previously published or written by another person except where due acknowledgement is made in the text.

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Abstract

An economic breeding objective was defined for unpruned radiata pine grown to produce structural grade timber flitch and high brightness newsprint from thermomechanical pulp (TMP) in Australia. A production enterprise model was developed including all sources of income (sale of flitch and newsprint) and costs (including growing, harvesting, transporting and mill processing components). The enterprise, as modelled, was shown to be profitable (*Profitability Index* 19.9%, assuming a discount rate of 5%). The majority of wood volume was assumed to be utilised to produce high brightness newsprint (77% by volume), with only 23% used to produce rough green flitch. The effect of future changes in growth, bark volume, stem sweep, stem taper, branch quality, timber strength, basic density, tracheid length, tracheid coarseness and wood brightness (breeding objective traits) on the profitability of this production enterprise was modelled by defining profit functions relating each of these traits to the economics of each stage of production. Sensitivity analysis was employed throughout this process to examine which assumptions were driving profitability, and identify any that may need verification. For each trait an economic weight was estimated as the incremental *Profitability Index* associated with a unit increase in each trait.

Basic density, mean tracheid length and wood brightness were demonstrated as having a major effect on the production of high brightness newsprint from TMP. Growth, as expected, had a large impact on the cost of growing a plantation, however was predicted to be only of moderate to low importance in increasing enterprise profitbability overall. Branch index was shown to have a major impact on the profitability of the flitch production line of the enterprise. Bark volume, stem sweep, stem taper and tracheid coarseness appeared to have a very low impact on production system profitability. However, the importance of stem sweep and stem taper as well as branch index and timber strength are likely to become more important if the enterprise increases its production ratio of flitch to newsprint.

An investigation into multi-trait selection strategies clearly demonstrated the dominance of basic density as a selection trait on enterprise profitability. The assessment of wood and tracheid properties is much more costly than assessment of growth and form traits. However it was demonstrated that the gains predicted from individual-tree selections compared with selection based on family-means for basic density and tracheid length are significant and well worth the additional associated cost.

Dedication

I would like to dedicate this thesis to the brave and gentle people of Tibet, who have suffered and are still suffering one of the great tragedies of our time. In particular, I dedicate this thesis to His Holiness the Dalai Lama who has peacefully fought against the systematic campaign of genocide in his country and against a world that has turned its back to Tibet through fear and greed.

To the weathered, kindly, but nameless lama at Sera Monastery who took the time to give his blessings to an interfering and pesky traveler, and in those brief moments may just have changed his life.

Photograph taken by the author at Sera Monastery in Tibet (November, 1998)

May the Tibetan people soon regain the sovereign freedom they have enjoyed since the dawn of history. May HH the Dalai Lama and all Tibetans return to their homeland. May they be welcomed home with open arms and an open mind.

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Publications during this Thesis

Refereed Publications

1. Chambers, P.G.S., Borralho, N.M.G. and Potts, B.M. (1996). Genetic analysis of survival in *Eucalyptus globulus* ssp. *globulus*. *Silvae Genet.* **45**: 107-112.

2. Chambers, P.G.S. and Borralho, N.M.G. (1997). Importance of survival in short-rotation tree breeding programs. *Can. J. For. Res.* **27**: 911-917.

3. Chambers, P.G.S., Potts, B.M. and Tilyard, P.A. (1997). The genetic control of flowering precocity in *Eucalyptus globulus* ssp. *globulus*. *Silvae Genet.* **46**: 207-214.

4. Chambers, P.G.S. and Borralho, N.M.G. (1999). A simple model to examine the impact of changes in wood traits on the costs of thermomechanical pulping and high brightness newsprint production with radiata pine. *Can. J. For. Res.* **29**: 1615-1626.

Conference Proceedings

1. Chambers, P.G.S., Borralho, N.M.G and Potts, B.M. (1995). The genetic control of survival in *Eucalyptus globulus* ssp. *globulus*. In 'Eucalypt Plantations: Improving Fibre Yield and Quality' (Eds. B.M. Potts, N.M.G. Borralho, J.B. Reid, R.N. Cromer, W.N. Tibbits and C.A. Raymond). pp 233-234. Proc. CRC-IUFRO Conf., Hobart, 19th-24th Feb. (CRC for Temperate Hardwood Forestry: Hobart).

2. Chambers, P.G.S. and Borralho, N.M.G. (1996). Impact of survival as a selection trait on the productivity of short rotation tree crops. In 'Tree Improvement for Sustainable Tropical Forestry' (Eds. M.J. Dieters, A.C. Matheson, D.G. Nikles

and C.E. Harwood). Vol 1, pp 187-188. Proc QFRI-IUFRO Conf. Caloundra, 27thOct-1stNov. (QFRI, Gympie).

3. Chambers, P.G.S., Borralho, N.M.G., Banham, P.W. and Cox, R.E.(1997). Impact of wood selection traits on a thermomechanical pulping system using *Pinus radiata* to produce newsprint. In 'IUFRO '97 Genetics of Radiata Pine' (eds. R.D. Burdon, J.M. Moore). pp 155-159. Proc of NZFRI-IUFRO Conf., Rotorua, 1-4 Dec. (*FRI Bulletin No. 203*)

Research Reports

1. Chambers, P.G.S. and Greaves, B.L. (1999). The estimation of genetic parameters and breeding values for diameter and survival traits across two sites in *Eucalyptus nitens*. Technical Report for the Southern Tree Breeding Association. February 1999.

2. Chambers, P.G.S. and Greaves, B.L. (1999). *Eucalyptus nitens*: The estimation of genetic parameters and breeding values for diameter and pilodyn traits in Trials VRD 56, 57 and 58. Technical Report for the Southern Tree Breeding Association. May/June 1999.

3. Chambers, P.G.S. and Greaves, B.L. (1999). Selection index coefficients for STBA breeding values for an objective which maximises the profitability of a vertically integrated enterprise producing timber flitch and newsprint. Technical Report for Fletcher Challenge Paper Boyer. November 1999.

Articles currently in preparation

1. Chambers, P.G.S. and Banham, P.W. (*in prep.*). An investigation of the pulp properties of thermomechanical and kraft pulp blends. *Appita J.*

2. Chambers, P.G.S. and Greaves, B.L. (*in prep.*). Estimating an economic breeding objective for radiata pine grown to produce structural-grade flitch and high brightness newsprint. *For Sci.*

3. Chambers, P.G.S. and Greaves, B.L. (*in prep.*). Estimation of gain from multi-trait selection for an objective which maximises the profitability of a vertically integrated enterprise producing timber flitch and newsprint. *For Sci.*

Contents

Format of Presented Chapters

Most chapters of this thesis have been or are in the process of being published as scientific papers or industry technical reports. Each chapter retains the structure of the scientific paper or report as published, however the following changes and amendments have been made to enhance the general readability and hence the flow of the thesis:

- bibliographies have been removed and aggregated to a single bibliography at the end of the thesis;
- abstracts, summaries and general acknowledgements have been removed;
- tables, figures, equations and appendices have been renumbered according to the chapter number;
- cross-references to published scientific papers which are contained as chapters in this thesis have been changed to the relevant chapter reference; and
- minor amendments have been made to the text to support the changes described above and to maintain the general flow of the thesis.

Each chapter of this thesis has been presented such that it stands alone as a report of scientific research. As such, some tables, figures and text presented in earlier chapters are repeated in subsequent chapters.

Chapter 1

General Introduction

1.1 The Question: What is a good tree?

The first question for any tree improvement program, regardless of how this improvement is sought (i.e. through breeding or by silviculture) is to decide on *what defines improvement*? In other words, tree breeders must decide on the program's objectives (Goddard 1998). All breeding programs have objectives, even if these are not quantified, and present only in the minds of the forest grower. However, the importance of a quantifiable economic objective in tree breeding cannot be overstated (Woolaston and Jarvis 1995, Shelbourne *et al.* 1997). As put by Amer (1994), the correct definition and quantification of a breeding objective 'will result in more return from breeding with no extra breeding effort'. Nevertheless, despite their importance to tree breeding, the formal development of breeding objectives to increase the profitability of enterprises based in forestry and the manufacture of forest products have appeared in the literature only recently (e.g. Borralho *et al.* 1993, Fonseca *et al.* 1995, Talbert 1995, Greaves *et al.* 1997, Shelbourne *et al.* 1997). However, breeding objectives are not an end in themselves but are part of a decision-making process (Goddard 1998). Important decisions that make use of a breeding objective are:

- the choice of individual trees as parents; and
- the evaluation of investment in breeding programs.

The first decision requires that the breeding objective must lead to selection criteria, while the second requires that the breeding objective must be related to predicted genetic changes. It is highly desirable that the same objective is used for both decisions (Goddard 1998) and to accommodate this, the breeding objective

must be written in terms of traits that apply to individuals or groups of individuals and in which genetic changes can be predicted.

The breeding objective will usually be to increase the profit of the firm, industry, or society that is investing in a breeding program (Goddard 1998). This objective should include long-term genetic gain and nonadditive genetic changes such as inbreeding depression and possibly a weighting against the variability of outcome. The breeding objective is described by a profit function that takes genetic values as input and produces estimates of profit as outcome. It seems to be the current consensus to base the profit function on a bioeconomic model with the estimation of covariances used in choosing selection criteria (Goddard 1998). The traits in the profit function should relate as directly as possible to all sources of income and costs. The profit function may include variables controlled by management decisions if these interact with genetic merit. The differences between genotypes should be evaluated when management variables are optimised for each genotype. In the long term, mean profit is expected to be close to zero, and all costs are assumed to be variable costs (Epp and Malone 1981). Under these conditions, the relative economic weights are equivalent (Amer and Fox 1994), regardless of how the unit for which profit is calculated, or whether the perspective (see Moav 1974) is that of individual producers, an industry, or consumers (Goddard 1998). However, if price signals are not passed along the chain from consumers to seedstock breeders, the economic weights may become distorted (James 1982).

For forest trees in general, the production system includes two major components:

- growing trees in the forest; and
- the conversion from this raw wood resource into the desired end product.

From a forest manager's perspective, the profitability of growing trees has been well established. Historically the "*best*" trees have been selected for having high growth (Figure 1.1), stem form and branch characteristics: faster growth because the trees will reach a desirable size sooner, or because a given forest estate will yield more wood on a sustainable basis; stem form and branch characteristics because these will influence the value of the mature forest for sawing. The influence of such traits on the costs of plantation establishment, maintenance, harvesting and transport has been demonstrated (e.g. Namkoong *et al.* 1969, van Buijtenen and Saitta 1972, Porterfield 1976, Cameron *et al.* 1989, Borralho *et al.* 1993 and Greaves *et al.* 1997). Thus, traditionally, one of the main objectives of tree breeding programs is to increase plantation productivity. One factor, identified by Borralho *et al.* (1993) as potentially having a major impact on plantation productivity was survival. However, survival has rarely been included in the breeding objective (e.g. Borralho

et al. 1993, Greaves *et al* 1997), despite the known variation and some evidence that it is under strong genetic control (Volker *et* al. 1995, Chambers *et al.* 1996).

Because plantation establishment and maintenance costs must be compounded to the end of the rotation, any factors affecting rotation length, especially growth rate, effectively control profitability of the forest growing phase (Shelbourne *et al.* 1997). However, variation in wood quality affecting product values, although long suggested to likely have a dominant effect on the profitability of processing and marketing end products (Shelbourne 1997), has until very recently been largely unexplored. Indeed, improvement of end-product traits due to the value-added-effect may have far more impact on total profitability than improvement of tree-growing traits (Greaves *et al.* 1997, Shelbourne *et al.* 1997, Greaves *in review*) particularly for vertically integrated industries. Further, the current problems with processing and marketing wood from fast-grown, intensively managed, shorter-rotation plantations have added impetus to a new thrust to genetically improve wood quality and hence end-product value (Shelbourne *et al.* 1997).

Figure 1.1- "New Zealand 55", approximate age 20: a high-growth selection (source of original photograph unknown*).

* Photograph scanned from A4-sized photograph taped to a wall in CSIRO Forestry and Forest Products, Canberra.

1.2 General Methodology

The works of Hazel and Lush (1942) and Smith (1936) led to the land-mark paper of Hazel (1943), where the key concept of aggregate genotype, or breeding objective was formulated. The aim of this concept was not just to predict the breeding value of a single trait but to predict that of a composite of several traits evaluated in economic terms. Hazel (1943) defined an objective that was a linear combination of traits in which the coefficient of each trait was its effect on profit when all other traits were held constant. This coefficient may be defined as the economic value, or more commonly the economic weight of each trait toward the total profitability of the objective. Thus the aggregate economic value of a genotype (H) as defined by Hazel (1943) can be approximated following:

$$H = w_1 a_1 + w_2 a_2 + ... + w_n a_n \qquad (1.1)$$

where:

- H is the aggregate value of the genotype (breeding objective)
- a_1 to a_n are the breeding values of the i^{th} trait; and
- w_1 to w_n are the economic coefficients (weights).

The traits represented in the breeding objective should include all the main components of profitability of the entire production system (Goddard 1998), regardless of whether or not they are easily measurable or heritable (Woolaston and Jarvis 1995).

The major steps in the development of a breeding objective were given by Ponzoni and Newman (1989) following Ponzoni (1986). This methodology may be summarised for the case of firms dealing in forestry and forest products as:

- specification of the breeding, production and marketing systems;
- identification and definition of the wood-flows and the sources of income and cost;
- determination of biological traits influencing wood-flow, income and cost; and
- derivation of the economic value (or weight) of each trait and the formal definition of the breeding objective function.

Although a wealth of published work exists for the development of animal breeding objectives, there is still relatively little reported work in the area of breeding objectives relating to forest trees. The implications of trait change on the utilisation economics of loblolly pine were explored by van Buijtenen *et al.* (1974). Chollet and Roman-Amat (1986) derived a breeding objective for *Pinus pinaster* grown for veneer based on growth rate and stem sweep. Borralho *et al.* (1993) derived an objective for *Eucalyptus globulus* grown for pulp based on growth rate, basic density and kraft pulp yield. This remains a landmark paper in the forest tree breeding literature. Greaves *et al.* (1997) applied the economic methodology of Borralho *et al.* (1997) to *E. nitens* including a stem form trait and a refined kraft pulping-cost model. Talbert (1986) set out the steps of formulating a breeding objective and selection index for tree breeding using a 10 year-old Douglas fir progeny test example. This author critically examined the selection index approach for a typical tree breeding situation with multiple traits and with information from multiple relatives, and argued strongly in favour of the full breeding objective/selection index approach.

1.3 Structure of the Thesis

This thesis is concerned with definition of a breeding objective for radiata pine in south-eastern Australia. The production system upon which this definition is based is assumed to be a vertically integrated enterprise growing radiata pine to produce structural grade flitch and high brightness newsprint from thermomechanical pulp. A major aim in the production of this work was to attempt to bring together information from different sources in order to reach more general conclusions which clearly have important practical implications for tree breeding. Therein lies the strength of this thesis. However, where gaps or uncertainty existed in the information required to formerly define a breeding objective for the enterprise under consideration, research was conducted to shed light on these areas. Still, in many instances, educated guesses were required to fill in current 'gaps' in our knowledge which would otherwise not allow a formal definition of the breeding objective to be achieved. For this reason, sensitivity analysis was employed throughout the thesis to verify any key assumptions made and to indicate where further work may be needed.

Following the methodology of Ponzoni and Newman (1989), an understanding of the various components of the overall production system, is a necessary step in the development of a breeding objective. In line with this methodology, Chapter 2 presents a brief introduction to the process of thermomechanical pulping and newsprint manufacture and the assessment of pulp and paper quality. Special

reference is made, wherever possible, to radiata pine throughout. Particular emphasis is placed on a review of previous work relating various wood and fibre characteristics to the energy consumed during refining (a major TMP production cost) and key paper quality issues (which define the specific grade, and hence market sector for which the paper product is sold). The effect of wood properties on solid timber strength is also briefly introduced.

Chapter 3 investigates the pulp properties of various thermomechanical pulp (TMP) and kraft pulp blends derived from radiata pine. Adding kraft pulp to TMP in newsprint manufacture is a routine practice and is aimed at improving the flaw-carrying ability of the newsprint sheet. However, the interaction between kraft pulp and TMP is not well explored, especially at low concentrations of kraft pulp (Kärenlampi 1995). Further, there is always a desire to minimise the addition of kraft pulp due to its large expense, relative to that of TMP (Seth and Kingsland 1990). Laboratory handsheet assessments of various blends of TMP and kraft pulp were conducted at Fletcher Challenge Paper's Boyer Mill (formerly Australian Newsprint Mills), providing an understanding of the behaviour of such pulp blends. From this analysis, a regression model was formulated in Chapter 4 relating the changes in two key strength parameters – tear index and tensile strength to the amount of kraft pulp required to achieve these changes.

Chapter 4 develops a model relating the impact of changes in wood traits on the costs of thermomechanical pulping and high brightness newsprint production. A pulping study was conducted across a wide range of wood samples at Fletcher Challenge Paper's Boyer Mill, for which wood and tracheid properties were also assessed. This enabled significant wood and tracheid properties to be related phenotypically to the pulp and paper quality traits assessed. In turn, relationships were also developed, using stepwise regression procedures, between TMP production system costs and the pulp and paper quality traits. Chapter 5 presents an analogous, but earlier piece of work to Chapter 4, relating tracheid length, tracheid coarseness, basic density and wood brightness to the costs of low-grade (as opposed to high brightness) newsprint production from TMP. The work presented in this chapter is not as detailed as that presented in Chapter 4 as it has been included exactly as published in a conference proceedings.

Chapter 6 provides a review of the current consensus for the definition of breeding objectives and the uses of such objectives. A basic introduction to the prediction of breeding values and a description of how to define the breeding objective profit function were described. A brief history of the debate surrounding several issues (for example, how to define profit, the unit for which profit is calculated, the perspective from which profit is viewed, bioeconomic models versus the estimation of economic weights by multiple regression etc) is presented and the contemporary

consensus on how to deal with these issues is described. The review was completed prior to formally defining a breeding objective for radiata pine, the formulation of which closely followed the guidelines presented in this chapter.

The relationships derived in Chapters 4 and 5 examined the impact of several significant wood traits on the costs of thermomechanical pulping and newsprint manufacture. Although useful in gauging the relative effects of each of these traits to this specific process, it does not provide a complete picture of the full impact of these and other traits across a vertically integrated enterprise which grows, harvests, transports and processes its own logs into structural grade flitch and high brightness newsprint. The boundary of such a production system must incorporate all of these issues and must account for all sources of income and expense must be accounted for. As such, Chapter 7 presents a detailed model of an assumed production system utilising unpruned radiata pine to produce structural grade flitch and high brightness newsprint from thermomechanical pulp. All assumed sources of income and costs are included, based on long-term market averages for a characteristic vertically integrated enterprise operating in south-eastern Australia. As costs and incomes were incurred and received at different times throughout the 'lifetime' of the plantation (e.g. the production system included two thinning harvests at 15 and 20 years and clearfall harvest at 25 years), discounting was used, which gave each cost or income a relative equivalence in time.

Following the method of Ponzoni and Newman (1989), Chapter 8 examines the impact of a number of biological traits, including growth, form, wood and fibre traits on the profitability of the production system defined in Chapter 7. Economic weights, in line with the formulation of Hazel (1943) were estimated for each trait based on the production system model defined.

During the course of this thesis, a lack of published information on the genetic parameters of wood and tracheid properties was recognised. A small scale study examining the inheritance of tracheid transverse dimensions, tracheid length, wood density and wood brightness in radiata pine was undertaken based on data supplied by Colin Matheson (CSIRO Forest and Forest Products). This study is presented as Chapter 9. A list of genetic parameters was constructed from these estimates and a number of previously published estimates to obtain a list of 'standard' assumed parameters for use in Chapters 10 and 11.

Chapter 10 was based on a technical report prepared for Fletcher Challenge Paper. The Southern Tree Breeding Association (STBA) have a list of Breeding Values for growth, stem score, branch quality and basic density traits (selection criteria), which are available to full-partners of the STBA's radiata pine breeding program. Chapter 10 estimates selection index coefficients for each of these four selection

traits using the economic weights derived in Chapter 8 and a 'standard' set of genetic parameters. The genetic correlation between STBA selection criteria (assessed at age 10) and the objective traits defined in Chapter 8 (containing a component of age-age correlation) was considered. The similarity between the economic weights calculated in Chapter 8 for the currently defined production system and two sets of economic weights defined previously by the STBA was investigated. Further, a comparison of the relative ranking of breeding values using each of these sets of economic weights is provided.

Chapter 11 examines a number of multi-trait selection options for the enterprise defined in Chapter 8, utilising 10 year assessments of diameter (at 1.3m), branch quality, stem score, basic density, mean tracheid length and coarseness and wood brightness as selection criteria. This provided a complete picture of the relative importance of each breeding objective trait (as predicted by the various selection criteria) to overall enterprise profitability. A scenario is presented based on a budgetary constraint of $100,000 for the assessment of the selection criteria. Simulations of different selection strategies were generated using Monte-Carlo methods, allowing the total number of families from which to base selections, the total number of trees assessed per family and the presence/absence of selection criteria to vary. A recommended selection strategy, given this budgetary constraint is provided.

An increase in productivity in plantations is one of the main objectives for a forest grower. However, despite the potential loss in productivity in regions of poor survival, an account of this trait has rarely been included in the breeding objective (e.g. Borralho *et al.* 1993). Chapter 12 examines the genetic control of survival across two sites with high mortality in southern Tasmania, based on the framework devised by Chambers *et al.* (1996). Estimates of volume per hectare were devised, incorporating information on the selection trait diameter (at age five) and an account of survival ability at the same age. The ranking of predicted breeding values for volume per hectare (the breeding objective trait) based on diameter estimates alone were compared with the ranking of breeding values predicted using a combination of information on diameter and survival ability. Chapter 13 extends the work of Chapter 12 incorporating a productivity function derived for *Eucalyptus grandis* plantations in South Africa, to examine the effect of survival on the breeding objective trait volume per hectare under a number of different scenarios. The trends, although derived from a model specific for *Eucalyptus grandis* should be applicable for most short-rotation species.

Chapter 14 was completed very early on in the course of this PhD and examines the genetic control of juvenile flowering, discussing the implications this has on the possibility of basing selections on this trait to 'speed up' generation turnover and thus increase genetic gain per unit of time. Although this work was based upon plantation eucalypts, the concept of 'speeding up' generation turnover is a general one, applicable to all forms of genetic improvement.

Chapter 15 presents an overall summary of the findings of this thesis and suggests some areas where more work (or assumption verification) may be required. A number of outstanding issues are discussed. Chapter 16 is a general bibliography of all preceding chapters.

Chapter 2

A review of the thermomechanical pulping process and the assessment of pulp and paper quality with reference to radiata pine

2.1 An introduction to thermomechanical pulping

The process of thermomechanical pulping has been widely reviewed by various authors including Kurdin (1977), Ebeling (1980), Kärenlampi (1992) and Nyakuengama (1997). Smook (1992) provides a good basic outline of the process. There is still much debate over the theory of thermomechanical processing with some aspects described by Nyakuengama (1997) as speculative at most. Indeed, supporting this Stationwala *et al.* (1995) suggested that a complete understanding of the underlying mechanisms of wood pulping is still lacking. The controversy may, in part, be due to the lack of suitable techniques to characterise changes in fibres during refining (Ebeling 1980).

The commercial production of refiner mechanical pulp was initiated in the 1960's. Thermomechanical pulping was the first major modification of this process and is still largely employed to produce high-tear pulps for newsprint and board (Smook 1992). The heart of these systems is the disc refiner, which may include a double revolving unit, with each disc rotating in opposite directions. Other designs utilise a revolving disc opposite a stationary disc or a revolving double-sided disc between two stationary discs. The material fed into refiners is usually woodchips but may also include sawdust. The compressions and frictions operating between the discs soften the lignin contained in this wood material. The initial defiberising process may be described as the step-wise "unravelling" of the wood chips into smaller and smaller entities and finally into fibres.

There are a great number of physical configurations in refiners, however a discussion of these is beyond the objective of this chapter. Similarly a large number of operational variables have been demonstrated as affecting chip refining. Although not discussed in detail, Table (2.1) provides a summary list of some of these variables.

Table 2.1- Summary of variables which may affect chip refining

Main Factor	Variable
Raw Material	wood source (species etc)
	length of chip storage
	general pulp quality
	moisture
	freedom from foreign material
Plate Specifications	material of construction (metallurgy)
	pattern and taper
	disc diameter
Operational	pressure and temperature
	consistency (usually between 18 and 30%)
	applied load (gap between plates)
	chemical additives
	chip feed rate
	change cycle of plates
	disc rotational speed

Smook (1992) discusses chip quality (Table 2.1) as an important factor affecting mechanical pulp quality. He suggests that green wood makes better pulp than dry wood and that bark or dirt may carry through the pulp. In addition odd sized wood fragments, especially from compression wood may cause problems in feeding the refiner and with heat penetration. Several stages of cleaning (washing) and screening usually occur prior to the chips being refined to account for these factors.

Thermomechanical pulping involves steaming the pre-screened and pre-washed chips at a temperature of 110^{0}C under atmospheric pressure. This softens the lignin in the middle lamella of each fibre-fibre bond, thus facilitating fibre separation and defibration is carried out at 100 to 170^{0}C and 350 to 450 kPa (Rydholm 1965, Kurdin 1977). As shown in Table (2.1), the refining temperature is one of a number of operational variables which determines the ease and pattern of fibre separation and hence the amount of electrical energy consumed during refining (Atack 1976, Sinkey 1979). The glass transition temperature (T_g) is the temperature at which lignin transforms from a solid state into a soft and flowing form without structural variation (Irvine 1985). If refining is carried out at

temperatures above the T_g, the fibres are easily separated because the lignin has undergone a dramatic softening. However, the released intact fibres are coated with the soft lignin, which upon cooling reverts to a glassy state that becomes an obstacle to subsequent fibrillation of the separated fibres (Smook 1992). The lignin–encased fibres have inferior bonding properties because the lignin restrains them from further fibrillation and swelling. This has also been demonstrated as dramatically increasing the amount of energy consumed during refining (Atack 1976, Kurdin 1977, Hattula and Mannström 1981). When chips are refined at temperatures just below the T_g, lignin is sufficiently softened for good fibre separation, but fractures may occur in the outer layers of the secondary fibre walls (Keays 1975, Smook 1992). Nyakuengama (1997) discusses this in detail, stating that fibre separation occurs at the primary-secondary wall (S_1-S_2) interface resulting in rough cellulosic fibres that fibrillate well and have higher inter-fibre bonding potential and tensile strength (see Hattula and Mannström 1981).

The three functional stages of refining were identified by Atack (1971) and summarised by Kärenlampi (1991). During the initial stage, wood is subjected to cyclic compression and shearing stress and it is this stage that consumes most of the grinding energy. Stressing results in fatigue failure of the fibre wall matrix mainly in the S_1 layer, thereby exposing the polysaccharide rich S_2 layer (Nyakuengama 1997). During the second stage, fibres are loosened from the wood structure by a stripping or peeling action. The final stage involves developing fibre properties and is accompanied by fibre cutting and creation of fines.

From a previous review of the literature, Nyakuengama (1997) concludes that it is now generally accepted that refining has three main effects on wood. The first effect involves the creation of new surfaces by external, internal and molecular fibrillation (Fox 1980, Hietanen and Ebeling 1990). External fibrillation occurs when the middle lamellae are detached from the fibre surfaces (Fox 1980) and, as described by Nyakuengama (1997), the tangential splitting of the coaxial of fibres results in internal fibrillation. Molecular fibrillation involves dissolution of polymeric constituents of the cell wall (Hietanen and Ebeling 1990). The second effect of refining is the creation of new particles and fines from the fibre cell walls. These particles are derived from the S_2 and primary layers from fibre and microfibril cutting and splitting of the cell wall. The latter effect is important in enhancing fibre-fibre bonding and increasing specific surfaces for light scattering. The third effect of refining involves structural damage of fibres.

Fibre development is the term commonly used in mechanical pulping to indicate the changes in the intrinsic wood fibre properties which occur during refining (Karnis 1994). Intrinsic fibre properties are independent of each other, and are important in determining the papermaking potential of a pulp (Heikkurinen *et al.*

1991). The intrinsic fibre properties are length, coarseness, width, wet flexibility, cell wall thickness and degree of collapse. Karnis (1994) found that the fibre development was characterised by delamination and peeling off of cell wall materials and the generation of fines. It must be noted that the delamination of fibres and the peeling off of the wall material in refining is not a recent revelation. For example, it has been observed in microscopic examination by many researchers (see Forgacs 1963, Mohlin 1977). Corson and Ekstam (1994) and Karnis (1994) discuss how the delamination and peeling action decreases both fibre wall thickness and fibre coarseness and hence simultaneously increase fibre flexibility and collapsibility. The delamination of the cell wall markedly reduces its thickness and, this phenomenon alone, accounts for more than 80% of fibre wall reduction (Johnson *et al.* 1995). Koljonen and Heikkurinen (1995) discovered that the hydrodynamic stiffness of only earlywood fibres decreased during refining, however as Nyakuengama (1997) discusses, the underlying mechanism of this remains shrouded.

When determining the amount of energy consumed during refining, Corson (1991) suggested that the ease of inducing "micro-cracks", compression and fibril removal from the cell wall during fibre development (characterised by internal and external fibrillation and creation of fines) might be of major importance (Nyakuengama 1997). This hypothesis was supported by Mohlin (1995), who suggested that the complex changes in fibre wall properties, fibre cross-sectional dimensions and the creation of micro-cracks in fibre surface layers which accompany fibre development accounted for a large portion of the applied energy in mechanical pulping.

As previously stated, the energy applied in refining disintegrates the wood chips at the entrance of the refining zone to produce coarse fibres and fibre bundles (Atack 1984); primary fines (consisting of ray cells and wood dust) are also produced (Karnis 1994). High-speed cine-photography has shown that matchstick-like particles entering the refining zone are randomly orientated (Nyakuengama 1997). However the majority of fibres within the refining zone are tangentially orientated in order to minimise resistance (Atack *et al.* 1989), and this orientation also directs the stresses caused by the disc bars along the fibre length (Kärenlampi 1991). Marton *et al.* (1980) expressed that the theoretical amount of energy necessary to separate fibres was only a small fraction (approximately 7%) of the total energy input. Indeed, they further suggest that up to 80% of the overall refining energy is lost through the ineffective operation of refiners. From Table (2.1), the amount of energy consumed during fibre development depends on wood species. The sensitivity of mechanical pulping processes to wood species has forced mechanical pulp mills to exert significantly more control over their wood supply than the average kraft pulp mill (Rudie *et al.* 1994). For example, the wood morphology of softwoods allowed for a more efficient use of energy than that of hardwoods

(Hattula and Mannström 1981, Marton *et al.* 1980, Miles and Karnis 1994, Rudie *et al.* 1994). In particular, narrow hardwood fibres are viscoelastically stiffer and are separated by a narrow middle lamella but are more densely packed (Nyakuengama 1997), making them more difficult to separate which inflates energy consumption during refining (Hattula and Mannström 1981). Furthermore, the greater fibre length and easier fibre development of softwoods enable them to form stronger mechanical pulps than hardwoods (Corson 1991).

In summary, during the initial stages of mechanical refining, wood is defibred by cyclic compression and shear stressing and this consumes a substantial amount of energy (Nyakuengama 1997). Subsequent stages involve fibre development characterised by internal and external fibrillation, creation of fines and new surfaces by stripping cell wall materials and thus reducing both the thickness and stiffness of the cell wall (Nyakuengama 1997). This stage also consumes a substantial amount of energy. Therefore, Nyakuengama (1997) concluded that energy consumption during mechanical refining is influenced to a large extent by the properties of the wood raw material (i.e. wood density, microstructure, cell wall thickness and ultrastructure) and pulp fibre properties (e.g. the ease of microfibril removal, inducing micro-cracks, fibre collapsibility and stiffness). It is also apparent that operational parameters of the refiner significantly influence the amount of energy consumed in mechanical refining (see Table 2.1).

2.2 Measures of mechanical pulp quality

2.2.1 Laboratory scale versus mill scale assessment

TMP studies based on different scales (laboratory, pilot and mill) have important differences as outlined by Nyakuengama (1997). As a consequence of this, it is reasonable to assume that studies based on the same wood material may give different results depending on the scale. This has indeed been shown to be the case with a number of authors highlighting the operational scale difference in laboratory, pilot and mill scale studies (Sferraza 1987, Levlin and Sundholm 1984, Williams and McKenzie 1993). Laboratory scale studies have the advantage of being smaller and hence much cheaper and easier to control than mill scale studies. However the above authors have cautioned against the interpolation or extrapolation of laboratory scale experimental results to a mill scale. Levlin and Sundholm (1984) suggested that all investigations must be undertaken at a realistic scale due to the dynamic nature of assessing pulping suitability and the rheological properties of wood (Nyakuengama 1997). An option is to undertake

studies on pilot plant scale equipment, which realistically represents full-scale mill operations (Levlin and Sundholm 1984).

A number of operational differences between studies carried out at different scales have been summarised by Nyakuengama (1997) based on the works of Levlin and Sundholm (1984) and Mohlin (1995). For example, chippers differ in operational parameters affecting chip size distribution and in turn energy consumption (Table 2.1) and ultimately pulp and paper properties. It is also the case, that steam temperature and pressures differ between different scales of studies. Variability can be introduced by differences in the physical size of refiners, production rates, stock concentration in the refiner and the number of refining stages required to achieve a given range of freeness (Nyakuengama 1997). All of these differences in operational parameters result in a considerable degree of variation between studies of different scales, with a generally poor correlation of results between them (Mohlin 1995).

2.2.2 Canadian standard freeness

A number of studies have used a reference freeness, such as 100 Canadian Standard Freeness (CSF) to assess the suitability of fibres for paper manufacture (Sferraza 1987, Corson et al. 1989, Corson 1991). CSF is basically an arbitrary measure of the drainage properties of the pulp under specified conditions (McKenzie 1994). One problem with using CSF as an assessment of pulp quality, is that it is correlated positively with wood density and is therefore "biased" towards coarse, thicker fibres of high density wood (Nyakuengama 1997). McKenzie (1985) questioned the utility of freeness because it depends on operational parameters such as temperature, the head pressure of the fibre freeness tester and the size of the refiner used to pulp the wood. Another detraction from using freeness as an assessment of pulp quality was outlined by Nyakuengama (1997). He discusses that during refining, the pulp freeness can decrease rapidly in wood that defibrates easily or which produces a lot of fines from cell wall stripping and fibre cutting. Consequently, this wood may be judged desirable despite the fact that the resultant pulp would consist of flocs and is of poor fibre strength.

2.2.3 Sheet density

A number of authors in earlier studies used the sheet density as a benchmark to assess the suitability of fibres for paper production (e.g. Uprichard and Gray 1973, Kibblewhite 1980, Uprichard 1980). MacKenzie (1994) discusses the various procedures for measuring this property. However, the use of sheet density was criticised by many authors due to the fact that it depends on fibre distribution,

orientation and packing density, which ultimately depends on fibre type (Corson et al. 1989, Corson 1991).

2.3 Effects of wood on pulping and paper properties

The preceding sections support the notion that the term wood quality in mechanical pulping is specific to a number of issues, including refiner scale, the operational conditions of assessment and also to the reference criterion.

2.3.1 Effects of wood and fibre properties on TMP energy consumption

Various attempts have been made throughout the literature with different degrees of success to relate the wood characteristics to mechanical pulping of softwoods (e.g. De Montmorency 1965, Brill 1985, Corson 1991, Hatton and Johal 1994, Karenlampi 1992; Mihelich et al. 1972, Miles and Karnis (1995). De Montmorency (1965) examined the relationship of wood density to pulp properties for three wood species: black spruce, white spruce and balsam fir. Brill (1985) studied the effect of some raw material variables on the properties of spruce TMP. Corson (1991) attempted to correlate wood characteristics (like wood density) to pulp properties for radiata pine. Hatton and Johal (1994) examined the properties of refined pulps for juvenile and mature wood species, whereas Karenlampi (1992) reviewed the attempts made to relate spruce wood fibres to the properties of pulps produced from them. Mihelich et al. (1972) examined the role of wood quality as one of the major process variables in the manufacture of refiner pulp. Miles and Karnis (1995) analysed a number of wood quality parameters (including fibre length and coarseness) which were shown to affect energy consumption to a given freeness level.

As mentioned previously, wood quality is an elusive term and has not been adequately defined (Miles and Karnis 1995). Wood density and moisture content affect the operation of the mechanical pulping process since they produce variations in the flow (by weight) of wood. It follows then, that this affects the specific energy and therefore the quality of the pulp. However even when these parameters and other production parameters (as listed in Table 2.1) are under control, there are differences in energy-quality relationships not only for pulps produced from different species, but also for those produced from the same species (Miles and Karnis 1995).

From all the literature examining the effects of wood and fibre properties on thermomechanical pulping, no single property was shown to be clearly responsible for the variation in energy demand during TMP. However a large number of cross-related wood and fibre traits have been implicated. For example, the study by Miles and Karnis (1994) based on the reanalysis of data presented by Corson (1991) on radiata pine and of de Montmorency (1964) on Norway spruce, suggested that specific energy was positively correlated with initial fibre length. Furthermore, in the case of radiata pine using Corson's (1991) data, specific energy appeared to vary directly with fibre coarseness. Hatton and Johal (1995) showed that juvenile wood consumed more energy to refine to a specific freeness than mature wood in lodgepole pine (*Pinus contorta* Dougl.) on account of its lower coarseness. This result conflicts with the conclusions reached by Corson (1984) in radiata pine. According to Hatton and Johal (1995) the more flexible, shorter and finer fibres of lower density in juvenile wood were able to absorb more energy than mature wood. Consequently, energy consumption during refining increased as fibre coarseness decreased. Nyakuengama (1997) discusses that this reasoning is similar to that of Pearson (1983) in that low density wood (comprising earlywood fibres) preferentially absorbed more energy than thick walled fibres (comprised of latewood fibres). Rudie et al. (1994) discovered that juvenile wood required approximately 15% more refining energy to match the tensile strength of mature wood on account of a lower modulus of elasticity (i.e. lower stiffness). Karenlampi (1992a,b,c) extensively reviewed the role of wood fibre properties in mechanical pulping and concluded that juvenile wood required more refining energy than mature wood because of larger inter-tracheid bonding area in relation to fibre coarseness (Nyakuengama 1997). The low freeness of juvenile pulp was most likely due to a combination of the smallness of the fibres and the high degree of fibre splitting (Karenlampi 1992c). In addition, Karnis (1994) surmised that the coarser pine fibres required more refining then thin walled spruce fibres most likely due to the lower modulus of elasticity of the latter.

Hoglund et al. (1976) hypothesised that the stiffness and internal friction of wood influenced the energy consumed during repeated compression and shearing which occurred in mechanical refining. According to Hoglund et al. (1976), morphological variations in earlywood to latewood ratio, density and the amount of compression wood determined the stiffness of wood, which ultimately influenced the amount of energy necessary to deform it. Salmen and Fellers (1982) have suggested that the ease of fibre separation is related to the radial elastic modulus, while the ease of fibre development is related to the longitudinal elastic modulus of wood (Nyakuengama 1997). Puri and Higgins (1984) hypothesised that the energy consumed during TMP was associated with a reduction in torsional modulus and or in the product of torsional modulus and internal friction (Nyakuengama 1997).

Koch (1972) indicated that wood with a high percentage latewood content (characterised by thick, strong and inflexible cell walls) was very difficult to defibrate, requiring a considerable amount of electrical energy to refine (see also Kurdin 1977). Basic density was shown to be a reasonable indicator of TMP electrical energy demand, however Koch (1972) warned against its use as a predictor of energy demand because of the composite nature of the trait. For example, variation in density can be affected by a proportional change in the early-late wood ratio or alternatively from a change in the cross-sectional dimensions of one or both of the wood-types. Indeed McMillin (1968, 1969) found that the gross wood characteristics (basic density and latewood percentage) and growth rate of loblolly pine had no effect on refiner energy and hand sheet strength properties. Furthermore, basic density has been demonstrated to be poorly correlated with coarseness (de Montmorency 1964, Sferraza 1987, Corson 1991, Karenlampi 1992a, Uprichard et al. 1994). However as stated by Nyakuengama (1997) and also discovered by this author, a concise account of the reasons why basic density is not a good predictor of refiner wood properties, is still lacking in the literature.

Another wood property shown to have a significant influence on the energy requirement during refining is fibre wall thickness, however the exact mechanism appears unclear. Studies on the role of fibre wall thickness in TMP are not common due to the absence of an "on-line" method for measuring this wood property (Paavilainen 1994). However, Pearson (1983) suggested that fibres collapsed by a rolling action that produces fibrillation during refining. Consequently, wood with a large proportion of thick walled latewood fibres would consume more energy to bring about fibre collapse (McMillin 1969, Koch 1972, Sferraza 1987, Corson et al. 1989). This view, however, disagrees with those of other researchers (see Pearson 1983, Rudie et al. 1994).

From the work of Wimmer (1992), Verkasalo (1992) and Donaldson (1995), Nyakuengama (1997) discusses that the fibre cross-sectional dimensions in the tangential direction and the microfibril angle in the same direction could potentially be major sources of variation in the stiffness (modulus of elasticity) and hence energy consumption between softwood genotypes.

In summary, then, it seems from the literature that a number of wood properties may influence the amount of energy required during refining, and that fibre properties seem equally important. For example, refining energy increased directly with fibre coarseness (fibre wall thickness) and inter-tracheid bonding area. The stiffness and internal friction of wood, expressed as radial or longitudinal moduli of elasticity seem to be inversely related to specific energy. However, since the two moduli are directly related to the microfibril angle of the S_2 layer (Verkasalo 1992, Wimmer 1992), specific energy could also be inversely related to microfibril angle.

Basic density seems to be a good indicator, but not predictor of specific energy. As such, components of wood density (cell wall and fibre size and fibre tangential diameter) which also influence the stiffness of both solid wood and individual wood fibres (Nyakuengama 1997) may be more important in predicting energy requirements of wood than basic density, a solid wood property. In addition, lignin topochemical distribution across the cell wall has been demonstrated to have a large impact in determining strength and fracture patterns in the cell wall (Downes 1987, Downes et al. 1991a b, Donaldson 1995). There is speculation that abrupt changes in lignin concentration favour easy fibre separation and influence subsequent fibre wall development during refining (Nyakuengama 1997). This would imply that lignin topochemistry has an influence in determining energy consumption during refining

2.3.2 Evaluation of Pulp to Predict Paper Properties

To evaluate mechanical pulp for a particular end use it is necessary at some stage of the laboratory evaluation procedure to make hand sheets from the pulp and compare the properties of the test sheets to the properties of sheets made from furnishes known to give the desired properties in a commercial operation (see Chapters 4 and 5). In this process test sheets can be made to the conventional APPI standard, or on a full commercial scale papermachine (McKenzie 1994). Traditionally, furnish changes as well as capital investment decisions have, and will continue to be made, based solely on sheets made at these scales (Amiri et al. 1991). Obviously handsheet trials allow a larger number of variables to be examined, with less pulp than do pilot papermachine trials, but entail a greater risk in transferring the results to a full scale continuous operation. Some of this scale-up risk in handsheet studies exists because conventional handsheets have random fibre orientation and have surface properties very different from commercial sheets. In addition they are difficult to calender and to test print meaningfully (Amiri et al. 1991). However, Oländer et al. (1991) suggest that the method of preparing conventional handsheets to predict paper properties is reasonable unless the pulp is to be used in paper products with a high filler loading. This is particularly true of the optical properties since these properties depend not only on the optical properties of the pulp and filler, but also on the extent to which the structure of the sheet can be changed when fibres are replaced by filler (Oländer et al. 1991).

2.3.3 Effects of wood and fibre properties on paper properties

The effect of wood fibre properties on paper properties has been demonstrated qualitatively by several experimental studies (Seth 1990a b, Corson 1991,

Paavilainen 1993). There are also a number of mathematical models (see Smallhorn and Karnis 1992 as an example) relating the properties of pulp fibres to paper properties, but their exact prediction of paper properties based on the component pulp fibres is still far from perfect (Retulainen 1996). According to Smook (1992), the two most important fibre characteristics with an influence on paper properties are fibre length and cell wall thickness.

Fibre length is a commonly assessed trait with impact on paper properties (Nyakuengama 1997). Unpublished data from Australian Newsprint Mills have shown very high correlations (up to 90%) between the length of fibres in wood and the length of fibres in pulp handsheets. This relationship has been confirmed in the literature by many authors including Corson (1991). Intuitively in a paper sheet, a longer fibre will have more fibres crossing it and thus have a greater number of areas of interfibre contact. If these areas all contribute to the load-bearing capacity of the overall bond system, then the longer the fibre the more force will be required to pull the fibre free from the surrounding network (McKenzie 1994). Eventually, a point may be reached where the restraint imparted by the bonds is greater than the force required to break the fibre. In this situation, the fibre will break, rather than pull free and increased fibre length will have no more effect (McKenzie 1994). The work done in pulling a fibre free of the fibre network is a function of fibre length (work = force applied * distance), wheras the work done in breaking a fibre is independent of fibre length (McKenzie 1994). This has important implications with respect to the effect of fibre length on certain property relationships such as tear/tensile in paper.

As well as the direct effects of fibre length on the mechanical properties of paper, it also indirectly affects the formation of fibres within the sheet. As fibre length increases, the fibres are distributed less uniformly in the plane of the sheet because of their greater tendency to flocculate while in suspension. This leads to weak spots in the paper sheet where the grammage is lower than average. Alternatively, longer fibres can also bridge across weak or damaged sections of the sheet, providing improved durability (McKenzie 1994).

The tensile strength of paper is determined by the relative strength of the fibre and the forces holding it in place (Van den Akker et al. 1958). As interfibre bonding increases, the failure mechanism in all modes tends towards fibre fracture rather than interfibre bond rupture (McKenzie 1994). Indeed, even in lightly bonded handsheets, it has been found that one third or more of the fibres are broken in tension rather than pulled out of the network (Van den Akker et al. 1958).; thus fibre strength sets a limit on the strength attainable from any mechanical pulp (McKenzie 1994). Therefore the tensile strength of a fibre can be considered in terms of the extent to which the basic strength (itself a function of microfibril angle)

has been reduced by either natural (e.g. reaction wood) or process induced (e.g. blunt chipper knives) effects.

The tearing resistance of paper on the other hand, represents the work done in breaking those fibres which are firmly fixed into the fibre network plus the work done in pulling less firmly bonded fibres free of the network. Increased interfibre bonding leads to an increase in fibre fracture, resulting in an increase in tensile strength (from above) as more fibre support the maximum possible load. However, the effect of increased fibre fracture on tearing resistance depends on whether the work done in breaking the fibre is greater or less than the work done in pulling the fibre out of the network. This, in turn, depends on fibre length, with work done increasing as the length of the fibre increases. Hence tearing resistance is ultimately determined by fibre length. Indeed, Smook (1992) states that fibre length is virtually proportional to tear strength in softwoods.

The cross-sectional dimensions of a typical papermaking fibre can be described in a number of ways, the most common being a combination of fibre diameter, lumen diameter and wall thickness (McKenzie 1994). The cross-sectional dimensions of wood fibres may be explained in a similar way (Nyakuengama 1997). This is based on the assumption that the wood or pulp fibre is roughly circular in cross-section. A slight variation of this is to measure major and minor elliptical axes of both fibre and lumen. These numbers are then manipulated in various ways to produce indices such as the Runkel ratio (R):

$$R = \frac{(D_2 - D_1)}{D_2} \qquad (2.1)$$

where:

- D_1 is the diameter of the lumen; and
- D_2 is the external diameter of the fibre.

It follows then, that the maximum relative bonded area can be related to the ratio of D_1/D_2 (Mckenzie 1994). The actual bonded area and specific bond strength control the actual bond strength per fibre, however the maximum relative bonded area provides an indication of the bonding achievable under ideal conditions.

The ratio of fibre length to cell wall thickness is sometimes used as an index of relative fibre flexibility (Smook 1992). However a more specific indication of a fibre's behaviour is provided by its coarseness value. Fibre coarseness is another parameter related to cross-sectional dimensions, in this case. In terms of Equation 2.1 (i.e. fibre dimensions), fibre coarseness may be expressed as:

$$C = \left(D_2^2 - D_1^2\right) \tag{2.2}$$

This depicts how coarseness is related to the cross-sectional area of the cell wall and hence influences the total number of fibres present, the spatial configuration of the fibre network and the strength of each individual fibre. In terms of paper properties, McKenzie (1994) discusses that increasing coarseness reduces the bonding by reducing the number of fibre crossings, but also reduces the probability of fibre fracture by increasing the strength of each individual fibre.

Basic density of the wood from which the pulp is derived is often claimed to relate to subsequent paper properties (Echols 1973, Ferrand 1982). Translating basic density (DEN) into fibre dimensions, assuming that the fibre cross-sectional area is approximately circular, we can see that basic density relates to the ratio of cell wall cross-sectional area to total cross-sectional area (i.e. cell wall plus lumen). Hence:

$$DEN = \frac{\left(D_2^2 - D_1^2\right)}{D_2^2} \tag{2.3}$$

which is also known as the Muhlsteph ratio. As previously described, most recent literature indicates that density is of secondary importance in refining and a review of the literature shows conflicting reports of importance in paper quality. However most of these were based on chip basic density and none accounted for the intra-ring variation of traits (including density) as is presented in more recent studies (Nyakuengama et al. 1997). Again, the compound nature of basic density may make it a reasonable indicator but not predictor of paper quality issues.

Fibre coarseness (C) is defined as the mass of fibres per unit length, or:

$$C = \frac{W \times 1000}{N \times L_N} \tag{2.4}$$

where:

- W is the oven dry weight of sample (μg);
- N is the number of fibres in the sample; and
- L_N is the numerical average fibre length in millimetres.

However this definition may not be fully appropriate, as there is considerable variation in coarseness at a specified fibre length, despite a high correlation between the two propeties (Paavilainen 1993). Fibre coarseness may also be defined as:

$$C = A\rho \tag{2.5}$$

where:

- ρ is the density of fibre wall material, for a fibre with cross-sectional area, A, along its length and irrespective of cross-sectional shape (Seth 1990).

This second definition implies that fibres are coarser, stiffer, less flexible and have less fibre to fibre bonding area and are less complient when they have thick walls (Nyakuengama 1997). A flaw in this second definition is that large fibres with thin walls which are highly collapsible have a similar coarseness value as small fibres with thick walls (Paavilainen 1993). Despite the imperfections in the definition of fibre coarseness, sheets with coarser, thicker fibres were demonstrated as being weaker in tensile strength but were stronger in tear (Seth 1990, Retulainen 1996). Paavilainen (1993) also found that fibre coarseness, when used as a synonym of fibre wall thickness, accounted for over 80% of the total variation in tensile and tear strength. According to Seth (1990), the formation index of a random sheet was proportional to the square root of fibre coarseness, at constant mean grammage, fibre length and width. This implies that doubling coarseness worsened the sheet formation by 40% (Nyakuengama 1997). Paavilainen (1993) also found that fibre coarseness (wall thickness) accounted for over 70% of the total variation in apparent sheet density and air resistance. At constant solids and fibre length, wet web tensile strength was inversely proportional to the square root of fibre coarseness (Seth 1990). For the case of hardwood fibres, Tamolang et al. (1967) estimated that cell wall area accounted for up to 89% of the variation in breaking load. Broderick et al. (1995) on a study of chemimechanical pulps , found that the available bonding area was positively correlated to fibre length and specific surface. Fibre bonding, swelling and bond strength were related to lignin content and fibre coarseness. Fibre strength was shown to depend on fibre coarseness and fibre width. Fibre elasticity depended on the same properties as fibre strength and on fibre length and specific surface. Also, fibre length and network continuity of paper depended on pulp fibre length fractions R14, R100 and R200 (Nyakuenmgama 1997).

Uprichard et al. (1994) found that burst and tear indices were positively correlated with radial modulus of elasticity and Young's modulus. Further, the paper strength properties were inversely related to the microfibril angle. Uprichard et al. (1994) also showed that higher lignin content strongly decreased paper strength properties, which concurred with the later findings of Broderick et al. (1995) and Lehto (1995).

Retulainen (1996) examined the basic properties of fibre strength, length, width (or diameter), coarseness and specific bond strength (SBS), relative bonded area (RBA)

and light scattering coefficient on the characterisitcs of the paper sheet. He surmised that much of the potential light scattering is due to the fibre lumens which may collapse during papermaking. Also approximately 20-60% of the fibre surface in paper is typically engaged in fibre bonding and hence does not contribute to light scattering (McKenzie 1994). Despite this, Retulainen (1996) showed that by reducing fibre coarseness, the light scattering properties of the resulting paper sheet would be increased. At a certain RBA and tensile strength, the absolute non bonded outer surface area of low coarseness fibres is lower than that of high coarseness fibres. This means that the light scattering coefficient of low coarseness fibres at a given tensile strength is higher than that of high coarseness fibres. Retulainen (1996) discusses the effect on paper properties of fibre coarseness and cross-sectional dimensions. He concludes that by avoiding unnecessary bonding could bring large improvements in optical properties. Light scattering coefficient (s), together with light absorption coefficient (k) and basis weight determine the opacity (reflectance) of the paper sheet. However, it is the light scattering coefficient which has the greatest effect on opacity (McKenzie 1994).

In summary, a number of physical wood properties directly determine suitability for mechanical pulping and paper production. However, the effect of most of these properties is vague due to the inter-relationships between them. For example, fibre coarseness seems to depend on both fibre size and fibre wall thickness (Nyakuengama 1997), which in turn affect fibre bonding, strength and the optical properties of the paper sheet.

2.3.4 Effect of wood properties on solid timber strength

Wood properties that determine suitability for both mechanical pulping and solid timber strength seem to overlap (Shelbourne *et al.* 1997). For example, density is positively correlated with both the modulus of rupture (MOR) and the modulus of elasticity (MOE) of clear wood, below fibre saturation point (Walford 1991, Tsehaye et al. 1995). Structural timber is sold by F-grade which relates to the basic working strength (MOR) of the timber (e.g. F4 has a basic working strength of between 4.3 and 5.5 MPa). However, timber strength is machine stress-graded where strength (MOR) is predicted from measured timber stiffness (MOE). In radiata pine, cambial age is strongly related to both basic density and MOR and MOE (Mishoro et al. 1986, Walford 1991, Cave and Walker 1994). Valenzuela and Nakayama (1991) showed that radiata pine juvenile wood was up to 1.4 times more plastic than mature wood. The MOE of Japanese larch was shown to increase directly with density (Takata et al. 1992). According to Baillères (1994) the dynamic longitudinal modulus of elasticity (DLMOE) of Eucalyptus wood decreased with increasing microfibril angle and acid insoluble lignin content, however Downes (1987) and

Downes et al. (1991) found an opposite trend in juvenile radiata pine. Nyakuengama (1997) discusses that this discrepency is most probably due to the fact that DLMOE varies erratically near the pith due to the presence of reaction wood but also the difference in species. Kollman and Cote (1968) showed that MOE varied inversely with moisture content, below the fibre saturation point. Gerard (1994) showed that DLMOE declined with tree age, most likely due to the decrease in the vitality of cambial activity with age. This postulated decrease in cambial activity vitality would most likely be related to changes in wood morphology in response to the different mechanical requirements of the juevile and mature stages of living trees (Nyakuengama 1997). Both Baillères (1994) and Gerard (1994) showed that DLMOE initially increased then decreased with increasing distance from the pith, regardless of tree height. As discussed by Nyakuengama (1997), the radial profile of DLMOE with repsect to distance from the cambium was similar to the previous, however in this case DLMOE reached a maximum earlier the closer the crown. This would imply then, that wood nearer the crown is physiologically juvenile compared to that near the base of the tree bole (Nyakuengama 1997).

In summary, it seems that high lignin content adversely affects fibre flexibility and the longitudinal modulus of elasticity of wood fibres. The latter is also related to the microfibril angle of wood fibres depending on the species and physiological age.

Chapter 3

An investigation of the pulp quality of TMP and kraft blends

This chapter is currently being prepared for submission as:
Chambers, P.G.S. and Banham, P.W. (*in prep.*): An investigation of the pulp quality of TMP and kraft blends. *Appita J.*

3.1 Introduction

Many papermakers rely on the addition of relatively expensive kraft pulp to improve the flaw-carrying ability, and hence the runnability (or paper strength) of the newsprint sheet (Mohlin 1984). Kraft pulp addition is also used to modify other properties such as wet web strength and drainage (Kazi and Kortschot 1996). The extent to which these benefits are provided depends on the quality of the chemical pulp (i.e. its drainage qualities, wet-web strength, and dry sheet properties (Seth and Kingsland 1990).

Adding kraft pulp to thermo-mechanical pulp (TMP) in paper manufacturing is almost a routine practice (the amount varies from 0-15% in newsprint paper grades, to 40-50% in light-weight coated (LWC) paper grades – Retulainen 1992); nevertheless, there is always a desire to minimise the amount added. However, the interaction between TMP and kraft pulp is discussed very little in the literature, even though it is a well accepted fact that paper properties can not be predicted by

assuming a linear weight-proportion dependence of the properties of the blends on those orginal pulps (Mohlin and Wennberg 1984). There have been a number of studies on the properties of kraft-reinforced TMP sheets (Mohlin 1984, Retulainen 1992, Seth and Kingsland 1990) however Kazi and Kortschot (1996) reiterate the opinion of Mohlin and Wennberg (1984) in that there is still no satisfactory description of the mechanics of reinforcement. For example, several studies have shown that the tensile strength of a mixture of different kinds of pulp is often lower than could be expected linearly from the tensile indices of the components (Bovin and Teder 1971, Mohlin and Wennberg 1984, Retulainen 1992). A number of reasonable hypothetical explanations for this and phenomenon dealing with other traits have been provided in the literature (see Fernandez and Young 1994, Kärenlampi 1995a, Kärenlampi 1995b), however gaps still exist in these explanations. One identifiable gap in the current knowledge is how the properties of the kraft fibres influence the properties of the mixed pulp sheet containing only a small amount of kraft pulp.

It is a common practice to predict the properties of a two dimensional paper sheet from laboratory handsheet assessments measured in a single dimension (Smook 1992). Since the inception of physical testing programs of paper properties late in the 19th century, a wide variety of tests and test instruments have been developed (McKenzie 1994). Indeed some fifty standard test methods are described in Australian Standard AS1301. ISO5270 only suggests six tests to be carried out on laboratory sheets: bulking thickness and apparent density, tensile strength, tearing resistance, bursting strength, air resistance and folding endurance. Other tests relevant to a specific end-use may be carried out as appropriate (e.g. optical properties in newsprint, ring-crush of liner-board). In addition, the pulp drainage properties (freeness) are commonly assessed prior to the preparation of handsheets.

Due to the structure of paper – an assemblage of fibres, self-bonded in a viscoelastic network – a paper sheet's properties are highly dependent, as are the properties of the pulp suspension (McKenzie 1994). Hence a simple calibration of the measuring device is not sufficient to ensure accuracy of the test result. Handsheet and paper samples must be conditioned to standard atmospheric conditions prior to testing, however the moisture content and physical properties of the sheet will depend to a large extent on the previous history (Smook 1992). Paper, being a hygroscopic material, seeks an equilibrium moisture with the surrounding air. However, the final moisture content will depend on whether the sample approached the equilibrium from a more dry state or a more moist state. Thus, paper samples must be conditioned in a standardised environment (usually 23^{0}C and 50% relative humidity) if reproducible results are required. At equilibrium, most paper products acclimated within this environment have a moisture content between 7% and 9% (Smook 1992). It is much more difficult to

attempt to generalise the effects of relative humidity on paper (pulp handsheet) properties. However all the tests listed as standards from ISO 5270 are shown to vary with relative humidity, dependent also on the fibrous components of the sheet, refining, additives and sheet surface treatments (Smook 1992).

As alluded to earlier, paper has a definite "grain" caused by the greater orientation of fibres in the machine direction of the paper machine and by the stresses imposed during pressing and drying. The directionality of paper must be taken into account in measuring physical properties and for such strength measurements as tear, tensile and burst, strips of paper are cut in both directions for testing. The impact of directionality on optical properties is considered minimal (McKenzie 1994). However, as discussed by Smook (1992) the machine direction (MD) and cross direction (CD) strengths of a machine-made paper are closely related to the strength of a randomly orientated sheet made from the same stock furnish. Generally, the random sheet will yield test-strength values (*STR*) that are somewhere between the MD and CD values, according to:

$$STR_{(random)} = \sqrt{STR_{(MD)} \times STR_{(CD)}} \qquad (3.1)$$

This is the basis on which pulp handsheet assessments conducted in the laboratory provide a reasonable indication of the physical strength properties of a sheet of paper produced on a mill scale paper machine.

The primary aim of the work presented in this chapter was to examine the effect of adding varying degrees of kraft pulp to the pulp furnish on pulp handsheet strength parameters (as an indication of paper strength). However, in the testing of handsheet strength properties, a number of additional tests were performed for which results are presented. It was beyond the scope of the present work, however, to examine the fundamental properties of kraft and TMP fibres which determine the strength characteristics of a dry newsprint sheet. Care was taken in the current chapter to conform to APPI standard guidelines in the production of pulp handsheets so that results could potentially be reproduced and extended by other researchers.

3.2 Materials and Methods

3.2.1 Pulp Material and Furnish Preparation

Unbleached TMP and bleached, beaten kraft pulp were provided by Fletcher Challenge Paper (formerly Australian Newsprint Mills) from their Boyer Mill. TMP was collected from the mill site from a production storage tank prior to bleaching and was produced from radiata pine. Kraft pulp (produced also from radiata pine) is purchased by Fletcher Challenge Paper in packages of semi-dry stock and was collected from a post-refining storage tank, prior to mixing with other production pulps.

Various mixes of kraft/TMP blends were prepared on a fixed percentage volume basis, according to Table 3.1.

Table 3.1- Experimental furnishes prepared from TMP and kraft pulp supplied by Fletcher Challenge Paper (formerly Australian Newsprint Mills).

Furnish Treatment	Name	Furnish Composition
Control TMP	K0	0% KRAFT / 100% TMP
Treatment 1	K2	2% KRAFT / 98% TMP
Treatment 2	K5	5% KRAFT / 95% TMP
Treatment 3	K8	8% KRAFT / 92% TMP
Treatment 4	K10	10% KRAFT / 90% TMP
Treatment 5	K15	15% KRAFT / 85% TMP
Treatment 6	K20	20% KRAFT / 80% TMP
Treatment 7	K30	30% KRAFT / 70% TMP
Treatment 8	K50	50% KRAFT / 50% TMP
Treatment 9	K80	80% KRAFT / 20% TMP
Control KRAFT	K100	100% KRAFT / 0% TMP

3.2.2 Pulp Properties

Pulp properties of each control and treatment group were tested on the various pulp furnishes listed in Table (3.1). Measurements of pulp fibre length, coarseness and the percentage fines fraction of each sample were estimated using a Kajaani FS200 Fibre analyser. The percentage fines fraction was estimated from the Kajaani fibre length frequency distribution; fibres under 0.2mm in length were considered in this context as fines. Five measurements were estimated per sample, making 55 measurements in total.

The Kajaani FS200 Fibre analyser relies on the ability of cellulose to depolarise a polarised light source to measure the number of fibres in each of 144 separate length categories. A very dilute suspension of fibres (0.001% consistency) was poured into a small test chamber, then drained through a glass capillary tube under suction. In this process, the fibres are constrained to flow through the tube lengthwise and are measured by a series of photodiodes (Smook 1992). The resultant signal is analysed by a microprocessor to give the relevant statistics of each property.

The resistance of a fibre mat to the flow of water is an important pulp property with respect to pulp processing and papermaking. The classical method of determining this property is by means of the Canadian Standard Freeness (CSF) tester. CSF is widely used as an indication of a pulp's suitability or quality (see Chapter 2, Smook 1992). In most mechanical pulping processes, the energy input is adjusted to maintain the product freeness within a narrow range. The CSF is defined as the number of millilitres of water collected from the side orifice of the standard tester when a pulp suspension drains through the screen plate at 0.30% consistency and 20^{0}C. In the current chapter, Canadian standard freeness (CSF) was estimated according to APPI standards, with five readings conducted per sample.

3.2.3 Physical Handsheet Tests

For each control and treatment group listed in Table (3.1), two reps of eight 60g/m^2 handsheets were prepared over a two week period. This provided 176 60g/m^2 handsheets in the total experiment, with 16 handsheets per control or treatment group. In addition, one replicate of eight 40 g/m^2 handsheets were prepared for each control and treatment group listed (providing 88 40 g/m^2 handsheets in total). The 60g/m^2 sheets are more uniform and suited for friction testing and roughness and porosity measurement, while the 40 g/m^2 sheets are more sensitive to optical effects (i.e. for scattering and absorption coefficients and brightness estimation).

Pulp handsheets were prepared according to Australian standards (AS1301). They were dried overnight under restraint and subsequently conditioned for at least 48 hours in accordance with APPI standards. Mechanical testing of 60g/m^2 handsheets was conducted in a controlled humidity and temperature environment at Fletcher Challenge Paper's Boyer Mill. The standard evaluations were recorded including: tear strength, tensile index, roughness, porosity, and burst index on a conditioned weight basis. Optical tests performed on the 40g/m^2 handsheets followed a similar strict routine as the standard evaluations on the 60g/m^2 handsheets and were also estimated on a conditioned weight basis.

The grammage or basis weight of paper was determined by weighing a known area of handsheet. Caliper was then measured using a micrometer with specified foot area and squeeze pressure on the sheet. From the basis weight and caliper measurements, the apparent density and bulk of each was calculated.

Tensile strength was determined by measuring the force required to break a narrow strip of cut handsheet where both the length of the strip and the rate of loading must be closely specified. Bursting strength was determined by clamping a cut handsheet portion over a rubber diaphragm through which gradually increasing pressure was applied, and noting the pressure at rupture. Tearing strength (or "internal tearing resistance") was determined with the Elmendorf apparatus which uses a falling pendulum to continue a tear in the handsheet when force was applied perpendicular to the plane of the handsheet. The loss of energy (as measured by the height of swing of the pendulum) is related to the force required to continue the tear (Smook 1992).

Surface roughness was measured by the air flow which occurred across a metal annulus in contact with the handsheet. To obtain this reading accurately, both the contact pressure of the annulus and the air pressure within the annulus must be carefully controlled. Air porosity was determined with the same instrument by measuring the air flow through a known area of handsheet when using a specified pressure differential.

The brightness and opacity of $40g/m^2$ handsheets were determined by taking reflectance readings at the appropriate wave lengths of light. Brightness is measured as the reflectance value (relative to a magnesium oxide standard) in the blue region of the visible spectrum (specifically at a wave-length of 457nm). Opacity is generally calculated as the "contrast ratio" between the reflectance value of a single handsheet backed by a non-reflecting black surface and that of a pile of handsheets of the same material.

3.3 Results and Discussion

3.3.1 Pulp Properties

Table (3.2) presents the pulp properties of each control and treatment furnish of TMP and kraft pulp. It indicates that mean fibre length and the drainage properties (CSF) of the pulp furnish both increase, as expected with an increasing percentage ratio of kraft to TMP used. Likewise, increasing kraft percentage leads to a decrease in pulp fibre coarseness and a decrease in the percentage fines content of

the pulp furnish. However Figure (3.1) indicates that the average mean fibre length may not significantly increase from the TMP control (furnish CT) until the pulp furnish is composed of greater than 8% kraft pulp. A similar result was shown for the percentage fraction of fines in the furnish sample (Figure 3.3). It is possible that this phenomenon may be due to the poor precision of the experimental procedure, as such a small sample of each pulp furnish, of extremely low consistency is used in the Kajaani FS200 Analyser (see methods section of this chapter). Hence it is possible at low percentages of kraft, that the furnish sample used to measure these pulp characteristics do not even contain any of the kraft pulp fibres. This could undoubtedly be improved by increasing the number of replicates per sample. However, Figure (3.4) shows that the CSF, or the pulp drainage properties, steadily increase in a more or less linear fashion even at low percentages of kraft pulp. It has been demonstrated that the accumulating fines fraction is primarily responsible for a reduced drainage (McKenzie 1994, Smook 1992). Given the conflicting relationships in Figures (3.1), (3.3) and (3.4) at low percentages of kraft volume, this may support the hypothesis above, that the imprecision of the experimental procedure has contributed to the results obtained.

Table 3.2- Pulp properties of control (K0 and K100) and treatment (K2 to K80) samples of kraft/TMP blends (mean standard errors shown in brackets)

Sample	Mean Fibre Length (mm)	Mean Fibre Coarseness (mg/m)	Fines (%)	CSF (mL)
K0	1.71 (0.05)	0.286 (0.005)	36.3 (0.9)	121 (7.6)
K2	1.69 (0.04)	0.295 (0.004)	37.9 (0.9)	123 (9.9)
K5	1.66 (0.03)	0.254 (0.004)	34.2 (1.1)	187 (11.2)
K8	1.75 (0.05)	0.274 (0.005)	36.8 (0.7)	129 (8.5)
K10	1.97 (0.04)	0.266 (0.005)	33.4 (0.7)	157 (10.3)
K15	1.93 (0.03)	0.248 (0.004)	32.2 (0.8)	186 (13.4)
K20	2.28 (0.02)	0.271 (0.003)	30.9 (0.8)	192 (8.8)
K30	2.24 (0.03)	0.245 (0.003)	24.5 (1.2)	274 (10.9)
K50	2.24 (0.03)	0.204 (0.004)	25.6 (0.9)	291 (13.1)
K80	2.55 (0.04)	0.215 (0.005)	15.6 (0.8)	354 (8.2)
K100	2.51 (0.04)	0.207 (0.004)	10.3 (0.8)	457 (11.7)

Figure 3.1- Mean tracheid length (mm) versus the kraft present (percentage by total volume) in each sample. Error bars depict ± one standard error.

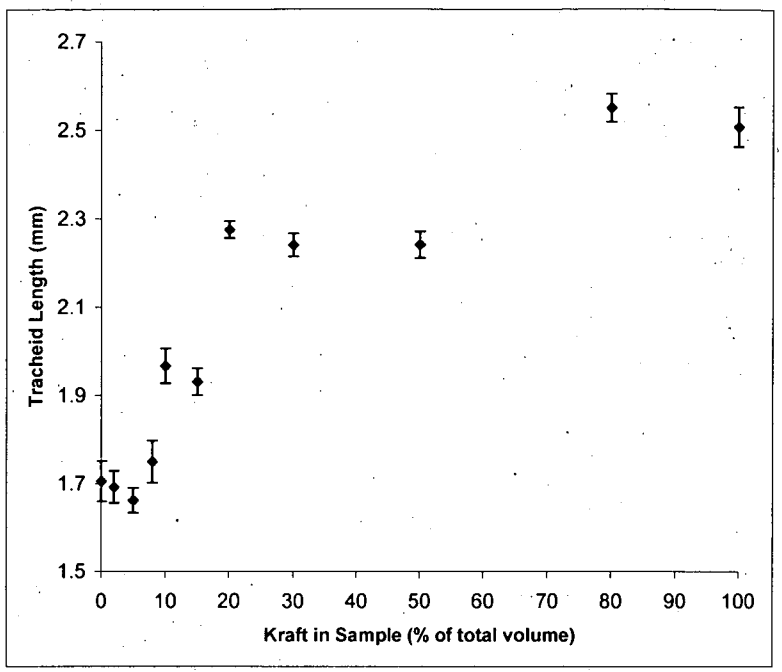


Figure 3.2- Mean tracheid coarseness (mg/m) versus the kraft present (percentage by total volume) in each sample. Error bars depict ± one standard error.

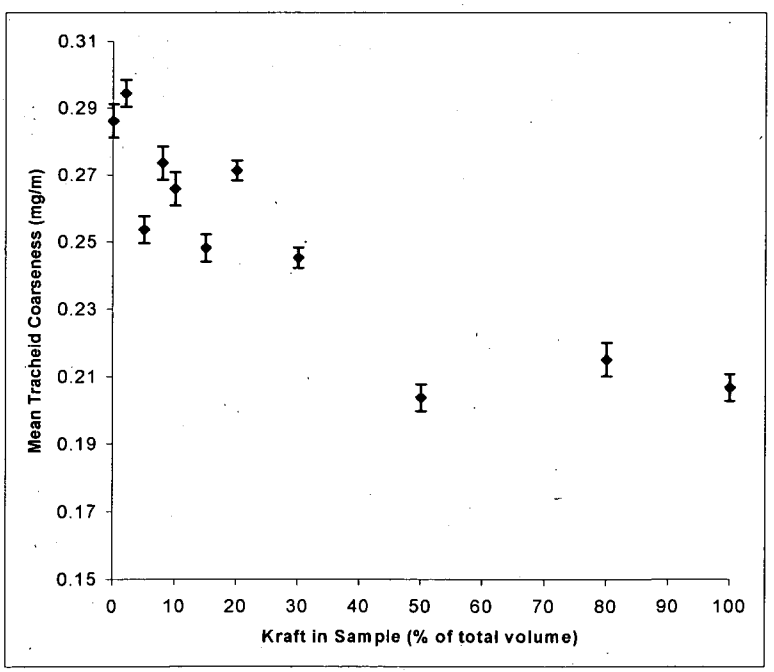


Figure 3.3- Fines fraction (percentage of total fibres analysed) versus the kraft present (percentage by total volume) in each sample. Error bars depict ± one standard error.

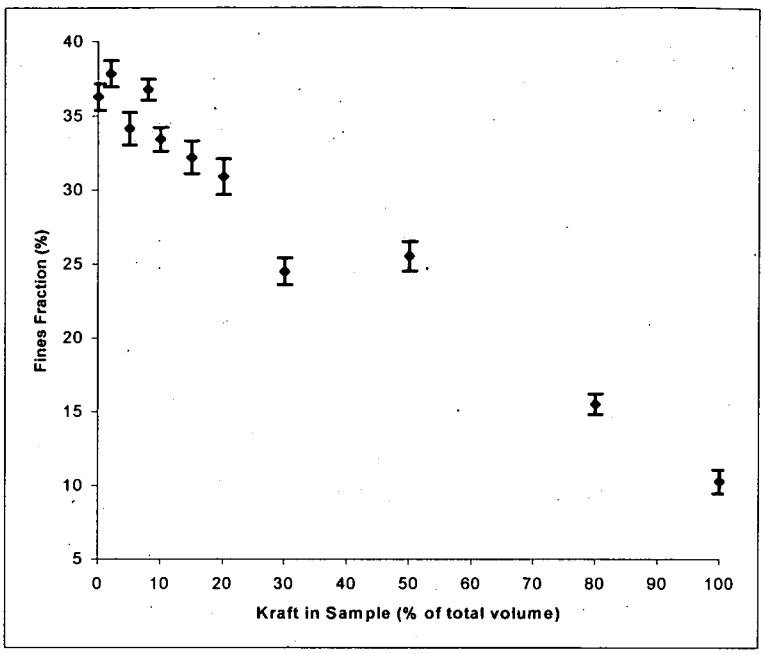
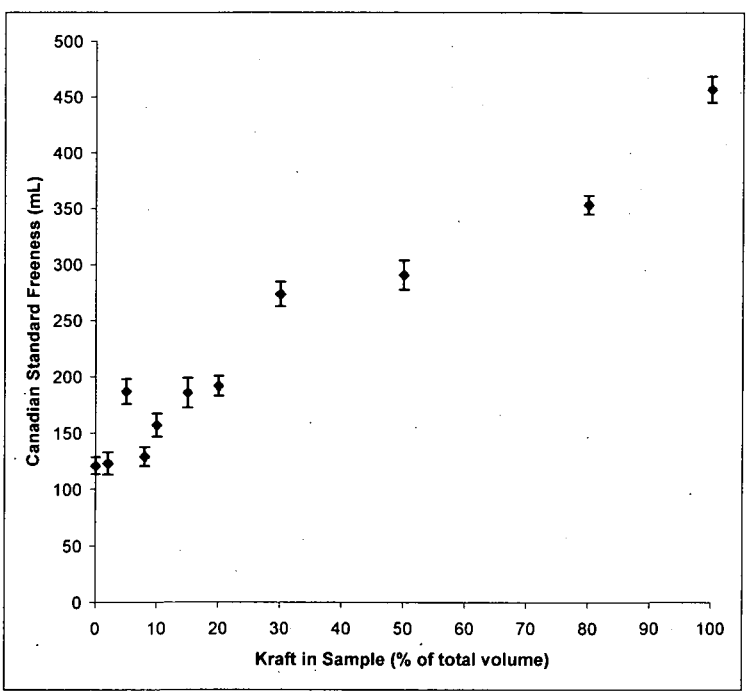


Figure 3.4- Canadian Standard Freeness (mL) versus the kraft present (percentage by total volume) in each sample. Error bars depict ± one standard error.



3.3.2 Handsheet Properties

The measured strength, optical and surface properties of 60g/m² handsheets for each control and treatment furnish are shown in Table (3.3). Optical properties measured for each control and treatment furnish using the 40g/m² handsheets are shown in Table (3.4).

Table 3.3- Pulp handsheet (60g/m²) properties of control (K0 and K100) and treatment (K2 to K80) samples of kraft/TMP blends (mean standard errors shown in brackets). (see text for further explanations)

Sample	TE	TN	SC	AB	BUR	ROU	POR	OP
K0	7.14	30.29	489.6	20.75	1.95	5.98	578.9	92.43
	(0.17)	(0.51)	(6.4)	(0.52)	(0.07)	(0.22)	(10.6)	(0.65)
K2	6.96	31.24	485.6	20.67	2.23	5.71	629.9	90.31
	(0.26)	(0.50)	(4.1)	(0.57)	(0.11)	(0.18)	(8.2)	(0.43)
K5	7.05	30.27	495.7	18.17	1.88	6.24	608.7	89.67
	(0.19)	(0.74)	(5.9)	(0.43)	(0.18)	(0.46)	(7.9)	(0.51)
K8	7.09	29.98	466.5	19.83	2.38	5.29	525.4	89.24
	(0.42)	(0.56)	(3.4)	(0.59)	(0.09)	(0.24)	(11.7)	(0.37)
K10	8.91	33.42	466.4	17.97	2.07	5.96	571.8	85.35
	(0.18)	(0.93)	(6.3)	(0.34)	(0.13)	(0.58)	(7.3)	(0.59)
K15	9.44	34.91	451.1	18.24	2.35	5.61	522.6	87.62
	(0.28)	(0.85)	(4.4)	(0.54)	(0.09)	(0.29)	(12.5)	(0.38)
K20	10.47	39.39	436.1	14.68	2.86	6.10	588.1	83.91
	(0..29)	(0.62)	(2.1)	(0.76)	(0.16)	(0.44)	(9.8)	(0.55)
K30	12.94	40.52	431.8	14.56	-	-	-	80.03
	(0.24)	(0.67)	(5.9)	(0.51)				(0.56)
K50	12.87	43.07	378.4	12.15	-	-	-	75.29
	(0.32)	(0.46)	(3.7)	(0.40)				(0.84)
K80	14.96	52.14	323.6	10.22	-	-	-	76.35
	(0.28)	(0.80)	(4.1)	(0.61)				(0.73)
K100	15.30	64.02	335.3	3.84	-	-	-	70.68
	(0.27)	(0.65)	(5.7)	(0.45)				(0.74)

TE is the tear strength (mN m²/g),
TN is the tensile index (Nm/g)
SC and AB are the light scattering and light absorption coefficients (measured as cm²/g) respectively
BUR is the burst index (kPa m²/g)
ROU is the surface roughness (mL/min)
POR is the handsheet porosity (g/m²)
OP is the percentage reflectance (%) of the handsheet

Table (3.3) shows that an increasing percentage of kraft pulp in the furnish leads to an increase in tear, tensile and burst strengths and a decrease in the light scattering and absorption properties and opacity of the pulp handsheets. No real trend was established for the surface roughness and porosity with increases up to 20% kraft in the furnish (up to treatment K20). Estimates of these surface parameters were not conducted for treatments K100 and T7 to T9.

Figure (3.5) shows that tear strength increases in a steadily linear fashion until the percentage kraft fibres in the furnish reaches around 30% and then tapers off. It would seem that at this point, enough kraft fibres are bonding with other kraft fibres in the furnish to convey a good proportion of the tear strength of the kraft

pulp control (furnish K100). Alternatively, tensile strength (Figure 3.6) increases steadily across the range of kraft pulp added, with the K100 control significantly superior to any other furnish in tensile strength. This would imply that the tensile strength of a thermo-mechanical pulp can be improved by the addition of more kraft pulp to the papermaking furnish, even if a sufficient level of tear strength has been achieved (Figure 3.7). This phenomenon indicates the interaction between tear and tensile strengths and is well documented in the literature (see Kibblewhite and Shelbourne 1996). Indeed, the reinforcement qualities of softwood kraft pulps are normally determined by handsheet tensile index/tear index relationships (Kibblewhite 1993).

Figures (3.5) and (3.6) both also show a common trend of tear and tensile at low levels of kraft addition however. It would seem from the results obtained, that the tear and tensile strengths of the pulp furnish are not improved to a significant extent until the furnish is composed of greater than 5% kraft pulp.

Figure 3.5- Tear Strength versus the kraft present (percentage by total volume) in each sample.

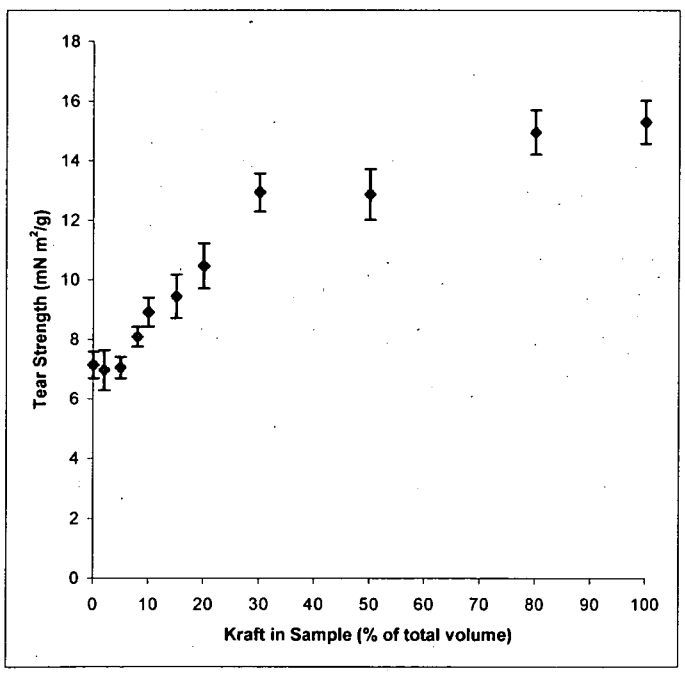


Figure 3.6- Tensile Index versus the kraft present (percentage by total volume) in each sample.

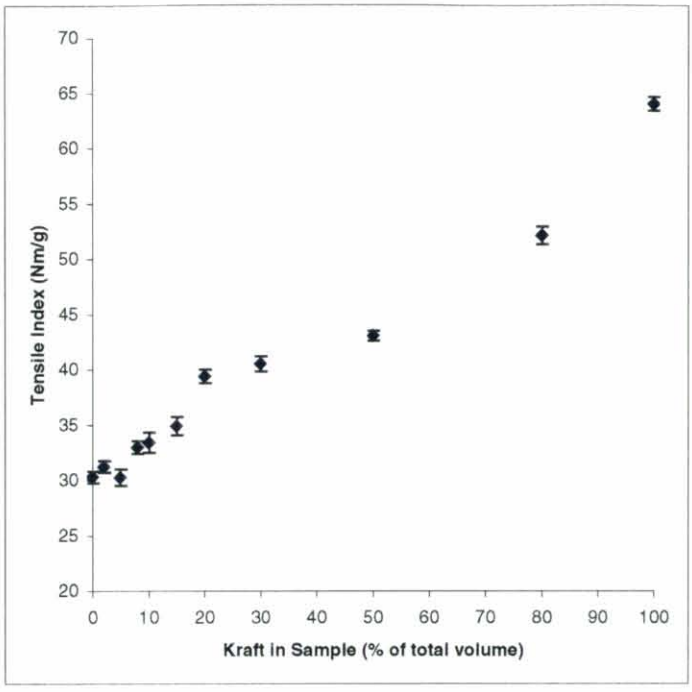
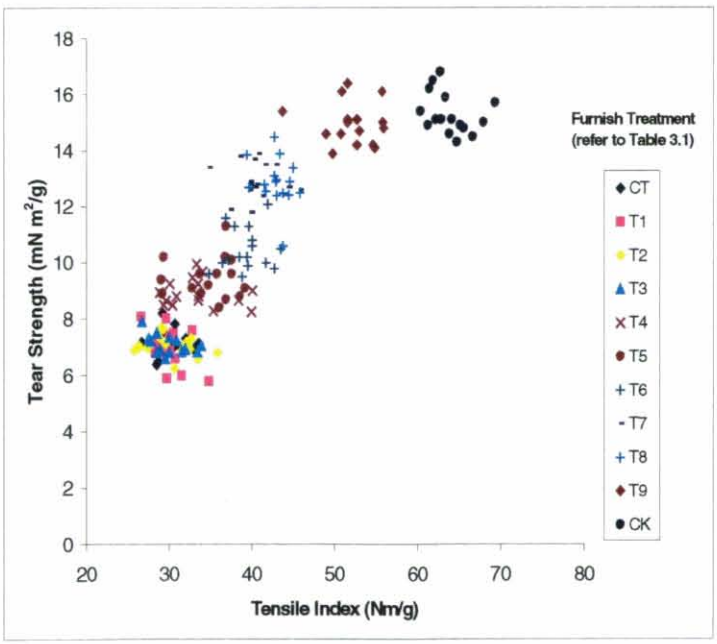


Figure 3.7- Relationship between tear and tensile strength across furnish treatments (increasing percentages of kraft pulp in the furnish)



Pulp fibre length was shown to be highly positively correlated with both tear and tensile handsheet measures (r^2 = 0.92 and 0.78 respectively), while the pulp fines fraction was highly negatively correlated with tear and tensile measures (r^2 = -0.87 and -0.91 respectively). Indeed, pulp fibre length has been demonstrated to influence the degree of fibre packing (Corson 1991), such that a longer fibre will have a greater number of areas of interfibre contact. Hence the longer the pulp fibre, the more force is required to pull it free from the surrounding network of fibres (Seth 1990, see Chapter 2). It follows then, that a greater number of fibres within a handsheet allow for a more even stress distribution in the sheet, promoting both tear and tensile measures (Broderick *et al.* 1996). Several studies have implied that fibre cross-sectional area plays a major role in determining the inter-bonding strength in a handsheet (see Chapter 2) and hence fibre coarseness may also be important in determining tear and tensile strengths. The results found in this study support this hypothesis, with strong correlations between both tear and tensile strengths and fibre coarseness (r^2 = -0.82 and -0.76 for tear and tensile strengths respectively).

Table 3.4- Pulp handsheet (40g/m^2) properties of control (CT and CK) and treatment (T1 to T9) samples of kraft/TMP blends (mean standard errors shown in brackets). SC and AB are the light scattering and light absorption coefficients (measured as cm^2/g) respectively, and OP is the percentage reflectance (%) of the handsheet (see text for further explanations).

Sample	SC	AB	BRG	OP
K0	455.2	18.94	53.58	80.01
	(7.4)	(0.61)	(0.56)	(0.54)
K2	418.9	19.35	52.59	82.46
	(5.3)	(0.38)	(0.65)	(0.38)
K5	447.5	18.17	53.58	80.97
	(4.1)	(0.49)	(0.55)	(0.49)
K8	442.7	16.59	55.95	78.41
	(6.7)	(0.55)	(0.60)	(0.68)
K10	457.4	17.54	55.71	75.36
	(3.6)	(0.89)	(0.57)	(0.52)
K15	422.9	15.33	59.01	77.10
	(5.1)	(0.74)	(0.45)	(0.42)
K20	401.8	13.86	57.28	65.29
	(6.4)	(0.31)	(0.60)	(0.78)
K30	408.6	12.97	58.98	68.53
	(5.3)	(0.94)	(0.66)	(0.91)
K50	362.1	10.04	75.85	61.47
	(4.7)	(0.75)	(0.78)	(0.45)
K80	312.7	6.68	90.10	60.07
	(4.2)	(0.66)	(0.69)	(0.37)
K100	293.7	3.55	92.31	59.42
	(3.2)	(0.42)	(0.60)	(0.53)

Table 3.4 and Figure 3.8 (overleaf) show that, as expected, ISO brightness increases with increasing percentages of kraft pulp in the furnish. This increase is slight at

low percentages of kraft pulp and occurs in a generally linear fashion. However, the effect of increasing percentages of kraft beyond the range of around 30% lead to dramatic increases in brightness. It would seem that the isolated kraft fibres within a network of unbleached TMP fibres have only a small effect on brightness at low percentages, but at higher percentages when whole networks of bleached kraft fibres can potentially be formed the effect on brightness is expectedly more pronounced.

Figure 3.8- Brightness versus the kraft present (percentage by total volume) in each sample.

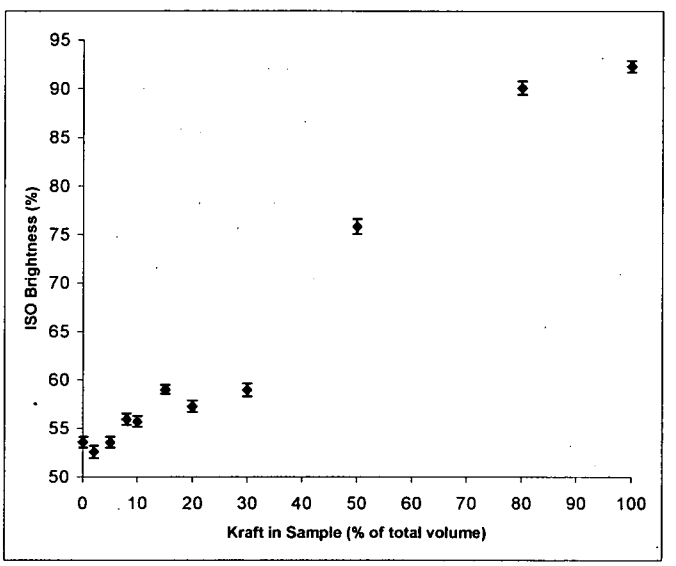
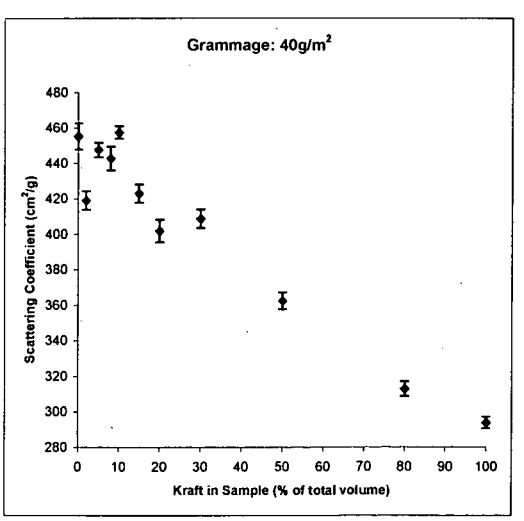


Figure 3.9- Light Scattering Coefficient versus the kraft present (percentage by total volume) in each sample.



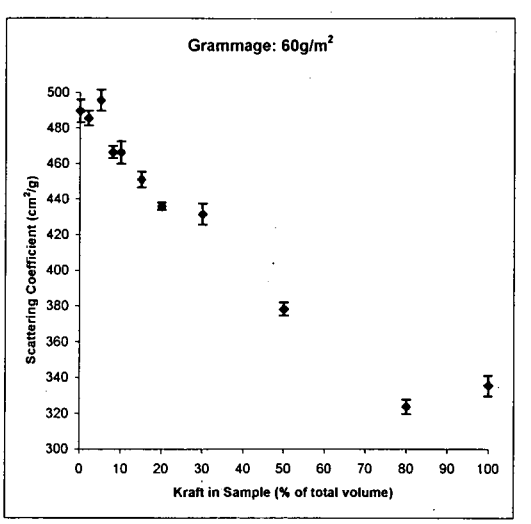
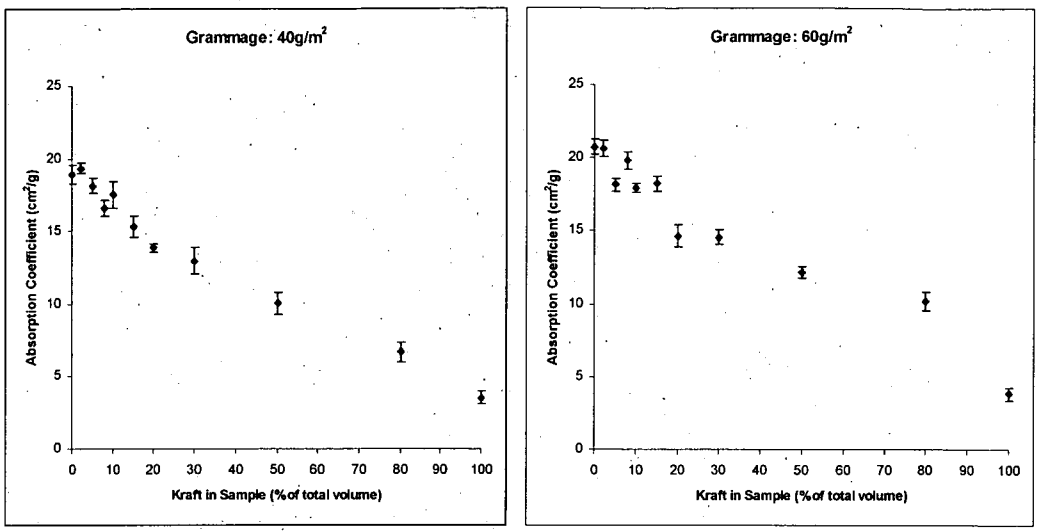


Figure 3.10- Light Absorption Coefficient versus the kraft present (percentage by total volume) in each sample.



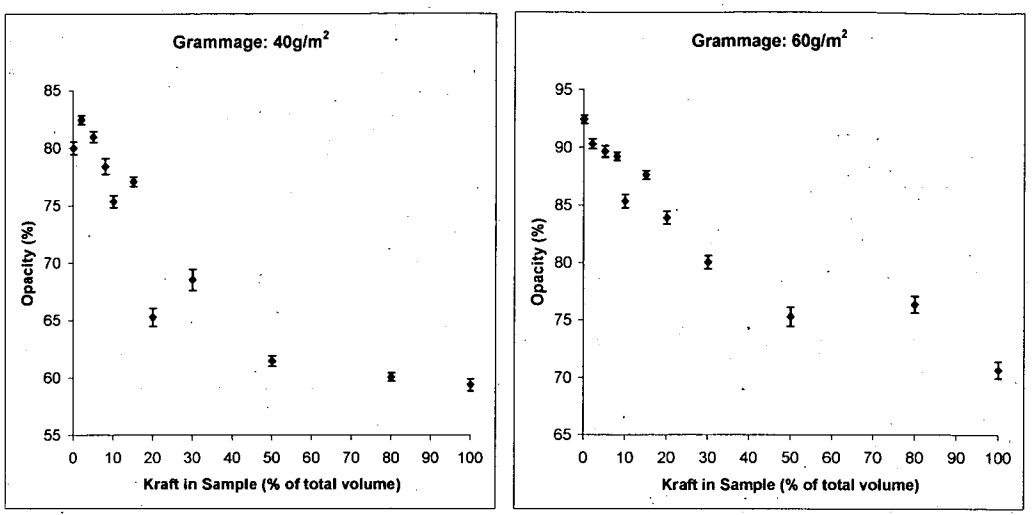
Figures (3.9) and (3.10) depict the effect of increasing kraft pulp on the light scattering and light absorption properties of 40g/m² and 60g/m² handsheets respectively. Increasing percentages of kraft pulp led to decreases in both the light scattering and absorption properties of the sheets tested. For the case of both traits, the trends were similar between the 40g/m² and 60g/m² handsheets, which increases the confidence with which these results may be viewed. Indeed the Pearson Rank Correlation between measurements made on a 40g/m² handsheet and a 60g/m² handsheet were 0.89 and 0.96 for the light scattering and light absorption coefficients respectively. A similar result was obtained in Figure (3.11) for the handsheet opacity, which is not surprising considering that this trait is derived via the Kubelka-Munk equations from the light scattering and absorption properties. Estimates of opacity for the 40g/m² handsheets must be considered with caution however, as the opacity measurements were conducted a full three weeks after handsheet preparation. Nevertheless, the Pearson Rank correlation between the estimates of opacity conducted on the two different grammage handsheets was high (0.92).

3.4 General Discussion and Conclusions

The results presented agree with those obtained by previous studies (e.g. Mohlin and Wennberg 1984, Seth and Kingsland 1990, Retulainen 1992) in that the properties of pulp blends of mechanical and chemical pulps can't be derived directly from the property levels of the original pulps. Tear strength and tensile strength deviate from the value calculated assuming a weight-proportion additivity

in the positive direction, while light scattering and absorption coefficients deviate in the negative direction.

Figure 3.11- Opacity versus the kraft present (percentage by total volume) in each sample.



The reinforcement qualities of softwood kraft pulps are traditionally determined by handsheet tensile and tear indices (Kibblewhite and Shelbourne 1997). This was the approach used in the current study of TMP and kraft pulp blends. However, this approach may be fraught with inconsistency since the separate effects of fibre length, wall area and perimeter are ignored and allowed to be confounded with one another (Kibblewhite 1993). Indeed, Seth and Kingsland (1990) describe the degree of fibre-fibre interaction and the presence of curl and microcompressions in the fibres as the major properties affecting the reinforcement properties of a kraft pulp. These were discussed in detail by Seth *et al.* 1984. Fibre properties such as length and fines proportion contribute to fibre-fibre interaction (Seth and Kingsland 1990).

Mohlin and Wennberg (1984), in a study of a number of different mechanical pulps concluded that these pulps interacted with chemical kraft pulps in a similar manner, independent of particle size distribution and bonding ability of the particles of the mechanical pulps. It was postulated that under most loading conditions, the two pulps in the furnish act as though they formed two almost independent networks. This was a very satisfying conclusion for papermakers, as it means that most of the optimisation work can be done on the original mechanical pulps and that their interaction with the chemical pulp in the blend does not need to be considered (Mohlin and Wennberg 1984). The partial incompatibility of the two pulp types was assumed to be caused by the very different behaviour of the

chemical pulp fibre and the mechanical pulp fibre during drying (Mohlin and Wennberg 1984, Seth and Kingsland 1990).

Most of the properties that determine the usefulness of paper are not physical absolutes. Therefore, measurements are often dependent on the instrument or equipment used and on the details of the testing procedure. The situation is further complicated by the fact that paper is both viscoelastic and hygroscopic. Since paper has both plastic and elastic characteristics, any test causing deformation or destruction of the sample (e.g. tear, tensile) will give results that are dependent on the rate of application of force. Seth (1996) recently outlined a process whereby softwood kraft pulp reinforcement potential in furnish blends can be optimised using tensile strength and other in-plane sheet properties such as elongation, Young's modulus and fracture toughness, rather than tensile index and the out-of-plane tear strength relationships. The Elmendorf tear test, although recognised as a good measure of fibre strength within the handsheet, has poor applicability as a gauge of pressroom runnability, where failures occur in the plane of the sheet (Smook 1992). Indeed Seth (1996) convincingly demonstrates the inadequacies of the out-of-plane Elmendorf tear test for optimising furnish blend compositions, processing requirements, and ultimate machine and paper conversion process runnabilities. However, Kibblewhite and Shelbourne (1997) discuss that tear and tensile relationships remain a useful and experimentally convenient indicator of softwood pulp reinforcement potential provided fibre dimensions are also taken into account.

The current chapter has shown that all handsheet strength properties increase with increasing proportions of kraft in he handsheet. However these gains in strength may not manifest until a minimum level of kraft fibres are present. Indeed, no overall increase in tear and tensile strength was observed until at least 5% kraft was added to the papermaking furnish. The brightness of handsheets also increased (light absoprtion and scattering coefficients decreased) with increasing percentages of kraft pulp, however again a minimum percentage of kraft pulp was required before any significant gains in brightness were observed. A very large gain in handsheet brightness occured only when a minimum of 30% kraft pulp was added to the furnish. These findings may have a significant impact on an enterprise seeking to minimise the costs incurred from adding kraft pulp to improve the reinforcement strength of newsprint. The findings suggest a minimum level of kraft fibres (5% by overall furnish volume) are required to significantly improve reinforcement strength of newsprint produced from thermomechanical pulp.

Chapter 4

A simple model to examine the impact of changes in wood traits on the costs of thermomechanical pulping and high brightness newsprint production with radiata pine

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4.1 Introduction

Despite their importance to tree breeding (Woolaston and Jarvis 1995, Shelbourne *et al.* 1997), the formal development of breeding objectives to increase the profitability (or similarly, to minimise the cost) of pulp and paper production have appeared in the literature only recently (e.g. Borralho *et al.* 1993, Chambers *et al.* 1997 – "Chapter Four", Dean *et al.* 1990, Fonseca *et al.* 1995, Talbert 1995, Greaves *et al.* 1997, Matheson *et al.* 1997). The major steps involved in the development of such objectives have been summarised by Raymond and Greaves (1997) following Borralho *et al.* (1993) and based on the work of Ponzoni (1986):

- to investigate the production system and develop an economic framework model;
- to identify components of the system that impact significantly on the total production costs;
- to develop equations relating the costs of production with relevant biological traits upon which selection pressure may be applied; and
- to derive the economic weights (economic value) of each biological trait

For forest trees in general, the production system includes two major components:

- growing trees in the forest; and
- the conversion from this raw wood resource into the end product.

The profitability of growing trees has been well established from a forest manager's perspective, where the breeding objective may be to simply minimise the cost of growing a cubic metre of wood. The impact of breeding under such an objective has been demonstrated to be strongly affected by improvements in survival, health, form, branch habit and growth rate and their influence on establishment, maintenance, harvesting and transport costs of individual trees (e.g. Namkoong *et al.* 1969, van Buijtenen and Saitta 1972, Porterfield 1976, Cameron *et al.* 1989, Borralho *et al.* 1993, Chapters 12 and 13, Greaves *et al.* 1997, Jayawickrama *et al.* 1997, Turner *et al.* 1997). However, variation in wood quality affecting product values, although long suggested to likely have a dominant effect on the profitability of processing and marketing end products, has until recently been largely unexplored. The prevalent problems with processing and marketing wood from fast grown, intensively managed, shorter rotation plantations (e.g. poorer strength properties) have added to the shift in focus to genetically improve wood quality and hence end product value (Shelbourne *et al.* 1997). The formal development of a breeding objective is critical for these purposes as it provides an accurate definition of where tree-breeding programs for such end products should be heading (Woolaston and Jarvis 1995). As put by Amer (1994), the correct definition of the breeding objective will result in more return from breeding with no extra breeding effort.

Hazel (1943) defined the breeding objective (or, the aggregate value of a genotype) as a linear combination of the genetic characteristics of an individual and the respective economic weights:

$$H = w_1 G_1 + w_2 G_2 + ... + w_n G_n$$

where:

- H is the aggregate value of the genotype (the breeding objective);
- w_1 to w_n are the economic weights; and
- G_1 to G_n are the genetic characteristics of the individual.

An economic weight may be described as the long-run economic advantage of a unit increase in a particular trait, assuming that there has been no change in any other trait.

Critical relationships between pulp and paper production costs and wood traits have been investigated for different pulping processes and for a number of species, including kraft pulping (Zobel and van Buijtenen 1989, Campinhos and Claudio-da-Silva 1990, Dean *et al.* 1990, Arbuthnot 1991, Borralho *et al.* 1993, Greaves *et al.* 1997) and cold caustic soak pulping (Banham *et al.* 1997). The current paper centres on developing such relationships and incorporating them into a high brightness newsprint production cost model for the thermo-mechanical pulp (hereafter abbreviated TMP) and papermaking process using radiata pine (Pinus radiata D. Don) as a wood source. Complex mill models are available for a number of pulping processes (e.g. Kerr and Uprichard 1976, Pu *et al.* 1991), and whilst useful for optimising pulping processes may not directly relate cost to changes in biological traits (Greaves *et al.* 1997). The current model has been developed for use by tree breeders in gauging the economic importance of a number of biological wood traits, which when combined with genetic information of these traits allows a breeding objective to be defined.

The development of the production cost model proceeded in four stages. Firstly, we related production costs to a number of pulp and paper quality (breeding objective) variables. These variables were identified from an examination of the thermo-mechanical pulp and papermaking process. Secondly, the pulp and paper quality variables were related to significant biological wood traits that can be measured, and hence easily selected for in the forest. The third step was to conduct an economic analysis of the impact that changes in values for each wood trait has on the total costs of production across the full phenotypic range of these traits. Finally a sensitivity analysis of the model was conducted using Monte Carlo simulation. This analysis seemed necessary as the information upon which this paper was based was drawn from a variety of sources, both experimental and personal communiqués. While most of the assumptions used are well supported, the approach taken has been to use the best available information from which to draw conclusions, then to explore the strength of these conclusions and identify key assumptions using the sensitivity analysis.

4.2 TMP and Paper Production Process

A schematic representation of the thermo-mechanical pulp and papermaking process is shown in Figure (4.1). This process is similar to the one used by Australian Newsprint Mills at their Boyer mill in Tasmania, Australia.

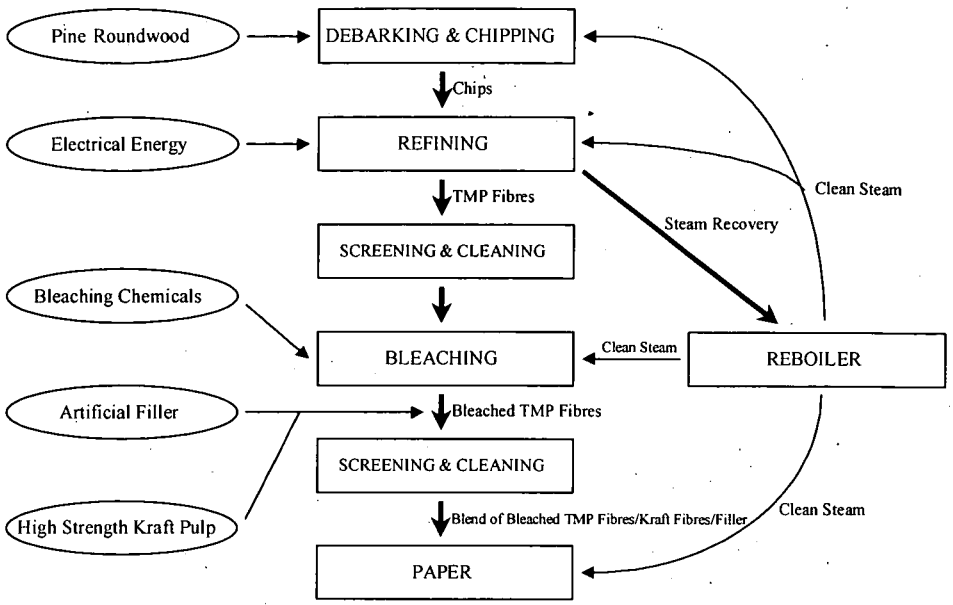
Pine roundwood transported from the harvesting site is debarked and chipped. These pine wood chips are then steamed under pressure just prior to, and during, mechanical refining. This steaming serves to soften the chips, which helps to reduce fibre breakage during the refining process. Refining (Figure 4.1) may be simply described as the step-wise "unravelling" of the chips into smaller and smaller entities, and finally into TMP fibres.

Once screened and cleaned, the TMP fibres enter the bleaching towers. A number of agents may be used during bleaching including lignin preserving or brightening agents (e.g. hydrogen peroxide). Other agents are added to optimise the conditions for the brightening agent (e.g. sodium hydroxide is used to maintain the pH during peroxide bleaching). Additional screening and cleaning stages may follow bleaching, before the bleached TMP fibres are blended with a non-fibrous artificial filler and a high strength kraft pulp. The finely divided white particles making up artificial fillers serve to fill in spaces between TMP fibres, improving the opacity of the paper sheet made from this TMP/filler mix. Adding fillers to the TMP also tends to promote the brightness, smoothness and density of paper sheets produced. The high strength kraft pulp is a reinforcement pulp, added to improve the paper strength properties.

The final pulp furnish which consists of a blend of bleached TMP fibres, kraft pulp fibres and filler particles (Figure 4.1) then enters the wet end of the paper machine, where it is carried through formers on a mesh belt. Excess water is removed and the fibres left behind bind together to form a wet web of paper. This wet paper sheet is then pressed and dried to make the final paper product.

The thermo-mechanical pulping process as a whole is energy intensive. Because of the relatively high temperature required throughout, most modern TMP mills have a system to recover a large portion of the process energy in a form that is useful in other sections of the process (Cropp 1991). Steam generated during the refining process is cleaned in a reboiling stage (Figure 4.1). Most modern TMP mills recover up to 75% of the energy put into refining and use it later in bleaching and paper drying stages (Smook 1992).

Figure 4.1- Simple schematic representation of the thermo-mechanical pulping and papermaking process.



4.3 Methodology

4.3.1 Total cost of pulping and paper production

The thermo-mechanical pulping and papermaking process detailed in Figure (4.1) was split into 3 simple stages of production which were seen to have a significant impact on the total costs of pulping and paper production (C_T) as follows:

$$C_T = C_c + C_r + C_q \qquad (4.1)$$

where:

- C_c is the cost of debarking and chipping green radiata pine roundwood;
- C_r is the cost of refining the roundwood chips;
- C_q is the cost of improving the quality of paper to a required product standard.

Due to the unpredictability of pulp prices, the competitive nature of the market sector and the fact that producers are mostly price takers, our model was simplified to minimising C_T, hence assuming prices for a specific paper grade to be constant.

Improving paper quality (C_q) was modelled as the cost of having a minimum acceptable standard, with most paper grades being defined by the market sector as a whole. Whilst there may be some advantages of improving quality above the minimum acceptable level such as improving market share or customer satisfaction, such do not translate into a premium in commodity prices, unless the paper is improved to such an extent that it may be sold as a higher grade. The current work corresponds to the production of a high brightness newsprint grade paper, with minimum pulp handsheet 'quality' characteristics assumed to be: tear strength (TE_m) of 9.0 mNm^2/g, tensile strength (TN_m) of 42.0 Nm/g, sheet brightness (PB_m) of 80% and sheet opacity (OP_m) of 92.0%. The cost of improving paper quality to these standards may then be defined as a function of three major components:

$$C_q = C_b + C_f + C_k \qquad (4.2)$$

where:

- C_b is the cost of hydrogen peroxide bleaching;
- C_f is the cost of improving opacity by the addition of a calcined clay filler; and
- C_k is the cost of strengthening the paper by the addition of a high strength 'reinforcement' kraft pulp.

The costs described in Equations (4.1) and (4.2) are operational costs and are expressed in US dollars per oven dry tonne of pulp produced. No distinction is made between fixed and variable costs of production as all costs can be considered to be variable in the long term (Epp and Malone 1981). This is a relevant assumption, particularly in the case of a breeding program, where benefits from genetic improvement in tree characteristics are not expected to accrue for 15 to 25 years (the time taken to select, collect, propagate, and grow improved genetic material).

4.3.2 Costs of Debarking and Chipping

The green volume of roundwood debarked and chipped is assumed to be constant and independent of changes in the wood traits examined. Although it has been demonstrated that the energy required to chip a given volume of green roundwood is directly proportional to the density of the wood (McKenzie 1970), the quantity of

dry material produced for a given volume is also directly proportional to density. Therefore the cost per oven dry tonne of TMP (odt.P) is unchanged:

$$C_c \cong z \tag{4.3}$$

where:

- z is a constant, given in dollars per oven dry tonne of TMP ($/odt.P).

Other wood traits such a stem straightness, or bark thickness may influence C_c, but they were not considered here.

4.3.3 Costs of Refining

The volume of chips entering the refiner is assumed to be constant and independent of the wood traits examined. It is also assumed that the energy required to heat chips prior to and during refining is generally constant and relatively independent of the wood traits. The cost of refining (C_r) may then be defined solely as the mechanical energy used by the process:

$$C_r = (E_m) \times c_r \tag{4.4}$$

where:

- E_m is the specific refining energy consumption, defined as the energy required to refine a pulp to 100ml CSF, expressed as kilowatt-hours per tonne (kWh/t) of pulp refined; and
- c_r is the cost per unit of energy ($/kWh).

4.3.4 Cost of Bleaching

The energy required to heat TMP fibres prior to and during bleaching was also assumed to be generally constant and relatively independent of the wood traits examined. Hence, the costs associated with the bleaching of TMP are assumed to be solely a function of the amount of hydrogen peroxide and sodium hydroxide required:

$$C_b = (p \cdot c_p) + (s \cdot c_s) \tag{4.5}$$

where:

- p is the amount of hydrogen peroxide added to the pulp in the bleaching towers as a proportion, c_p is the cost per unit of H_2O_2 ($/t);
- s is the proportion of sodium hydroxide (added in conjunction with the hydrogen peroxide to maintain an optimum bleaching environment); and
- c_s is the cost per unit of NaOH ($/t).

4.3.5 Cost of Filler Addition

It was assumed that there is no loss of clay filler from the system. Filler not directly incorporated into the pulp furnish is recovered with 'white water' recirculation. Hence, the cost of filler may be defined as:

$$C_f = (f \cdot c_f)-(w_f \cdot c_w) \quad (4.6)$$

where:

- f is the amount of clay filler added to the pulp as a proportion;
- c_f is the cost per unit of calcined clay filler ($/t);
- w_f represents the radiata pine roundwood fibre saved due to the addition of the non-fibrous filler (hence $w_f = f$); and
- c_w is the basic cost of radiata pine roundwood fibre ($/t).

4.3.6 Cost of Kraft Pulp Addition

It was also assumed that there is no loss of kraft pulp fibre from the system, due to 'white water' recirculation. The costs of adding reinforcement kraft pulp may hence be derived from:

$$C_k = (k \cdot c_k)-(w_k \cdot c_w) \quad (4.7)$$

where:

- k is the amount of kraft added to the TMP as a proportion;
- c_k is the cost per unit of imported kraft pulp ($/odt);
- w_k represents the radiata pine roundwood fibre saved due to the addition of the reinforcement pulp (hence $w_k = k$); and

- c_w is the basic cost of radiata pine roundwood fibre ($/odt).

4.4 Experimental

There were two main experimental elements in this chapter. The first was in the development of empirical relationships between paper quality traits and production commodities from operational mill data. The second was to develop relationships between paper quality traits and wood traits based on the processing of wood samples into pulp handsheets. This work was carried out at Australian Newsprint Mill's Research Department at the Boyer mill site.

4.4.1 Relationships between paper traits and production commodities

Empirical relationships were developed between paper quality traits and various commodities used to enhance pulp handsheet quality, using unpublished data from Australian Newsprint Mills Ltd. Tasmania, Australia. Commodities included hydrogen peroxide bleach to improve brightness, calcined clay filler to improve opacity and reinforcement kraft pulp to improve tear and tensile strength properties. The general underlying assumption in the development of these relationships was that the properties of a pulp handsheet provide a reasonable indication of the properties of a paper sheet. Although in reality, pulp fibres tend to align in the machine direction plane in the paper making process, affecting paper properties in different dimensions, the use of pulp handsheets to predict the relative strength and optical properties of paper is a convenient and inexpensive method which is widely accepted.

The effect of adding increasing proportions of hydrogen peroxide, clay filler and kraft pulp on the opacity, brightness and strength of a pulp handsheet were modeled using a range of linear and non-linear functions. The simplest inherently logical function of best fit was chosen in each case. 'Best fit' was judged intuitively in each case as the model with the highest r^2 value and stability across the range of each variable examined. With the costs per unit of each commodity known, this provided an objective method of quantifying the costs of improving paper quality . Models and data were validated by plotting the standardised residuals (residual / standard deviation) against fitted values, to ensure that no relation between these two sets of values was present. Normal probability plots were also constructed to determine if the assumption of Normality held within the range of the data used, and for evidence that a multiplicative model may be more appropriate to the data.

4.4.2 Relationships between wood and paper quality traits

4.4.2.1 Wood Material and Pulp Handsheet Assessments

Wood samples were collected from commercial production forests of *Pinus radiata* throughout Tasmania, Victoria and New South Wales, Australia. The age of wood samples varied from 10 over 50 years, covering a wide range of ages which may be expected to be used for thermo-mechanical pulping. These samples originated from one of three different sources collected over a two-year period:

- Sample A whole trees (with five trees pooled into one sample)
- Sample B slabwood (unchipped saw mill off-cuts)
- Sample C saw mill residue (pre-chipped wood mixtures)

The genetic relatedness of the five trees making up Sample A was unknown. Discs were cut at random from different parts of Samples A and B, with 7-8 strips cut from these discs for analysis of wood selection traits. These samples were then chipped, with a small quantity of chips put aside for further wood trait analysis. Wood selection traits examined for each sample were: mean tracheid length, coarseness, wall thickness, specific surface, radial and tangential diameters, and wood basic density and wood brightness. The SilviScan device (Evans *et al.* 1995) was used to analyse the strips from each sample, providing information on all traits, except mean tracheid length, wood basic density and wood brightness. Measurements of wood tracheid length (length weighted average length) and wood basic density were established from peracetic acid digestions of some of the wood chips put aside from each sample.

This technique (see Cox *et al.* 1996) involved the soaking of samples in hot aqueous sodium hydroxide solution, followed by washing and then partial delignification with hot (90°C) peracetic acid. A Kajaani FS200 fibre analyser was used to determine the length of tracheids in the peracetic acid solution. Wood brightness was measured by grinding the remaining wood chips into a powder and using an Elrepho 2000 spectrometer for analysis. Eighteen readings were conducted on ground chips per wood sample, and the average of these values used.

Similar investigations were conducted on the pre-chipped saw mill residue Sample C. However in this case, SilviScan analyses were conducted on the wood chips themselves as opposed to cut strips. Although not directly analogous to the SilviScan measurements conducted on Samples A and B, it was assumed the measurements would not be significantly different from these. Pooled mean values

and the observable range for each wood trait across all samples is shown in Table (4.1).

Table 4.1- Mean values, observable range and standard deviations of wood traits examined.

Wood Trait	Mean	Range	Standard Deviation
Tracheid Length (mm)	2.5	1.9 –3.5	0.296
Tracheid Coarseness ($mg.m^{-1}$)	0.50	0.41 – 0.63	0.045
Tracheid Wall Thickness (μm)	2.95	2.39 – 3.69	0.214
Tracheid Specific Surface (cm^2)	266	207 – 312	18.6
Tracheid Radial Diameter (μm)	34.1	31.1 – 39.1	2.39
Tracheid Tangential Diameter (μm)	30.6	28.0 – 33.2	1.46
Wood Density ($kg.m^{-3}$)	450	346 – 568	45.8
Wood Brightness (%)	50	44 – 55	3.07

Between 6 and 25 pulping runs were conducted for each wood sample depending on the amount of wood material available. Pulps were refined under pressure with a modified Sprout Bauer 12-ICP laboratory refiner to various levels of freeness (CSF), a measure of the drainage properties of the pulp stock and estimates of specific energy consumption (E), the energy required to refine a given pulp, were obtained. Freeness is widely used as an indication of pulp quality and is maintained on a commercial scale within a narrow range by adjusting the energy input of refining. From our experience, measurements of specific energy consumption from the laboratory scale refiner used, tend to be 20 to 25% higher than would be expected if the same sample was refined in a commercial sized refiner across the range of specific energy typically consumed in the thermo-mechanical refining process (Chambers, unpubl. data). Hence, the absolute values obtained for specific energy consumption from each pulping run were scaled down by 20% to gain a more realistic production figure. Pulp handsheets were produced and a number of strength and optical properties tested according to the Australian Standards AS1301. These properties included tear index, tensile index, brightness, opacity and light scattering and light absorption coefficients. To compare the pulp handsheet (paper) properties at a constant freeness, data from each pulping run was interpolated or extrapolated by drawing a regression line through the data points to 100 CSF. This gave a single data point for each pulp property that could be compared between wood samples.

4.4.2.2 Modelling Process

Relationships between wood traits and pulp handsheet (paper) traits were developed using multiple linear regression techniques with *PROC REG* in SAS (SAS,

1996). A backward stepwise elimination procedure was used to derive equations in which wood traits had to be significant at the 5% level or better in explaining the variation exhibited in pulping traits.

When constructing these equations, the tolerance values of significant wood traits were maintained at least at a value of 0.8 to ensure they were not too highly correlated, which would have made the estimates of the regression coefficients unstable. It was assumed that the linear regressions were appropriate to capture the relationships between biological wood traits and pulp handsheet (paper) properties, however care must be taken in the extrapolation of these relationships outside the specified range of each wood trait given in Table (4.1). Normal probability plots and plots of standardised residuals versus fitted values were constructed to check the model validity and data in each case.

4.5 Results and Discussion

4.5.1 Relationships Between Paper Traits and Production Commodities

Table 4.2 provides a summary of the functions which best fit the relationships between pulp handsheet (paper quality) traits and the proportion of each relevant commodity used to enhance these traits. The proportion of hydrogen peroxide (*p*) required to achieve a brightness of 80% was best explained by a non linear asymptotic function, such that increasing levels of peroxide were seen to have a diminishing effect on brightness. However, this function was simplified into a linear relationship without a significant decrease in the r^2 value, ($p \leq 0.05$) (Table 4.2), when looking at the reasonably narrow range of brightness used in this study. The proportion of sodium hydroxide (*s*) required is then a simple linear function of the proportion of p added (Table 4.2).

Increased levels of clay filler (*f*) in the pulp handsheet were shown to be directly proportional to improvements in opacity, up to a minimum level of 92% (Table 4.2). The amount of kraft pulp required to improve tear strength to minimum level of 9.0 mNm^2/g and tensile strength to a minimum level of 42.0 Nm/g was a more complex issue. As the proportion of filler in a handsheet increases, the strength properties tended to decline. The nature of this interaction can be grossly approximated by allowing for a 2% decrease in handsheet strength properties (N. Collins ANM, unpubl. data). A linear regression model developed from work in Chapter 3 was

shown to be significantly related to the proportion of kraft pulp required to attain the minimum strength properties specified (Table 4.2).

Table 4.2- Functions relating paper quality traits (brightness, opacity, tear and tensile strengths) to quality enhancement commodities. Where: PB_m is the brightness, OP_m the opacity, TE_m the tear strength and TN_m the tensile strength of pulp handsheets used to infer paper quality.

Quality Cost	Commodity	Function of Best Fit	*n*	*CV*	R^2	Range of Model Stability
Bleaching	Peroxide (*p*)	$p = (80\text{-}PB_m)/4.10$	40	29.9%	0.72	$2.0 \leq p \leq 7.1$
	Caustic (*s*)	$s = 0.05 + (0.77*p)$	40	9.4%	0.94	$1.6 \leq s \leq 5.7$
Filler Add^n	Clay filler (*f*)	$f = (92\text{-}OP_m)/1.25$	32	21.8%	0.76	$3.8 \leq f \leq 15.8$
Kraft Add^n	Kraft Pulp (*k*)	$k = \{2.5*(9.0\text{-}TE_m)\}+\{0.27*(42.0\text{-}TN_m)\}+\{0.20*f\}$	80	18.4%	0.73	$0 \leq k \leq 11.4$

4.5.2 Relationships Between Wood and Paper Quality Traits

Phenotypic correlations between wood traits, pulp traits and quality traits are presented in Table (4.3). A summary of the relationships developed is presented in Table (4.4).

Specific energy consumption at 100ml CSF was shown to decrease with either increasing wood tracheid length or wood density (Table 4.4). Other wood traits which showed a significant relationship with specific energy consumption ($p<0.05$) were tracheid wall thickness, tracheid coarseness and tracheid specific surface. This finding supports previous studies which have suggested that specific energy to a given freeness generally decreases with increasing wood density (De Montmorency 1965, Brill 1985, Corson 1991), and increasing tracheid length (Miles and Karnis 1995).

Table 4.3- Phenotypic correlations between the wood, pulp and paper quality traits examined. Significant correlations are depicted as either: *(p<0.05), **(p<0.01), or *(p<0.001).**

	Wood Traits								Pulp Traits				
	Tracheid Length[1]	Tracheid Coarseness[2]	Wall Thickness[3]	Specific Surface[4]	Radial Diameter[5]	Tangential Diameter[6]	Wood Density[7]	Wood Brightness[8]	Specific Energy[a]	Tear Index[b]	Tensile Index[c]	Handsheet Brightness[d]	Handsheet Opacity[e]
length[1]	-												
coarse[2]	0.44**	-											
thick[3]	0.43**	0.69***	-										
ssurf[4]	-0.47***	-0.60**	-0.97***	-									
radd[5]	-0.05^{ns}	0.75***	0.26**	-0.35**	-								
tand[6]	0.19*	0.44**	0.18*	-0.02^{ns}	0.48**	-							
dens[7]	0.38**	0.28*	0.96***	-0.85***	-0.29*	-0.58***	-						
bright[8]	0.24*	0.03^{ns}	-0.14*	0.18*	-0.05^{ns}	-0.02^{ns}	0.31**	-					
E[a]	**-0.52****	**-0.49****	**-0.48****	**0.48**	**0.07^{ns}**	**0.04^{ns}**	**-0.65*****	**-0.16***	-				
TE[b]	**0.69****	**0.68****	**0.64****	**0.65**	**0.04^{ns}**	**0.03^{ns}**	**0.42****	**0.08^{ns}**	-0.46**	-			
TN[c]	**0.31***	**0.18^{ns}**	**0.06^{ns}**	**0.04^{ns}**	**0.01^{ns}**	**0.01^{ns}**	**-0.02^{ns}**	**0.04^{ns}**	0.14^{ns}	0.39*	-		
PB[d]	**0.27***	**0.36***	**0.24***	**-0.13**	**0.25***	**0.01^{ns}**	**0.38***	**0.69*****	0.24*	0.18*	0.09^{ns}	-	
OP[e]	**-0.39***	**-0.63*****	**-0.58****	**0.49**	**0.05^{ns}**	**0.09^{ns}**	**-0.35***	**-0.45****	0.32*	-0.45**	-0.15^{ns}	0.27*	-

Both strength quality traits (tear and tensile) were also shown to be best explained by wood tracheid length and wood density. Increases in tracheid length resulted in increases in both tear and tensile strength, while wood density acted antagonistically increasing tear strength, but decreasing tensile strength (Table 4.4). The relationship between these two strength traits is complex and depends not only on the individual property of wood tracheids, but the nature of the pulp fibre network developed after refining. Wood samples with a greater mean tracheid length tended to produce pulp handsheets with a greater mean pulp fibre length (r^2=0.87, data not shown). Pulp fibre length influences the degree of fibre packing (Corson 1991), such that a longer fibre will have a greater number of areas of interfibre contact. Hence, the longer the fibre, the more force is required to pull it free from the surrounding network of fibres (Seth 1990). It follows then, that a greater number of long fibres within a handsheet allow for a more even stress distribution in the sheet, promoting both tear and tensile measures (Broderick *et al.* 1996). Wood samples of higher wood density however, also tended to contain tracheids with thicker cell walls (r^2=0.96 between wood density and tracheid wall thickness, Table 4.3), which are intrinsically stronger and less collapsible than tracheids from lower density wood. Assuming a high correlation exists between the wall thickness of tracheids and the wall thickness of pulp handsheet fibres, it may be expected that handsheet fibres developed from thicker walled tracheids, while being intrinsically stronger do not bond together well. This may be explained by their reduced collapsibility. Wood density would hence tend to affect tear and tensile strengths differently, as predicted by the model, reducing the bonding strength of the pulp fibre network, but increasing individual fibre strength.

Table 4.4- Best regression models relating significant wood traits to pulp and paper quality traits (as defined in Table 4.2).

Pulp Traits	Best Regression Model	*n*	R^2	s.d.	*CV*	Range of Model Stability
Specific Energy Consumption	E_m = 3748-(1.29**length***density*)	36	0.55	360 kWh/t	17%	1184 ≤ E_m ≤ 2900
Tear Strength	TE_m = -1.8+(1.33**length*)+ (0.015**density*)	44	0.76	1.12 mNm^2/g	12.9%	5.9 ≤ TE_m ≤ 9.0
Tensile Strength	TN_m = 36.1+(2.04**length*)- (0.013**density*)	44	0.38	3.49 Nm/g	13.8%	31.8 ≤ TN_m ≤ 42.0
Brightness	PB_m = 33.9+(0.52**bright*)	62	0.69	5.67 %	8.9%	50.7 ≤ PB_m ≤ 80.0
Opacity	OP_m = 68.2+{0.03*669- (357**coarse*)}	37	0.63	6.52 %	7.8%	80.5 ≤ OP_m ≤ 92.0

It has been suggested that the brightness of mechanical pulp is related to the colour of the wood it was produced from (Wilcox 1975, Zobel and Jett 1995). Hence an improvement in wood brightness is a possible way of improving the brightness and subsequently the bleachability of mechanical pulps (Wilcox 1975). The relationship established in the present study (Table 4.4) supports Wilcox (1975) hypothesis, showing that increases in wood brightness corresponds to increases in pulp handsheet brightness (r^2=0.69). No other selection trait showed significance at the 5% level in explaining the variation in pulp handsheet brightness.

Opacity may be simply defined as the characteristic ability of a pulp handsheet to hide from view any other non-active material placed behind it. Opacity was shown to be best explained solely by the coarseness of a tracheid (Table 4.4), such that a wood sample with coarser tracheids would tend to produce a handsheet of lower opacity (r^2=0.63). Previous work has shown that tracheid coarseness is significantly correlated to the light scattering properties of pulps (r^2=0.62, Chambers *et al.* 1997-"Chapter Five"), which in turn is a major determinant of opacity. Other significant variables included tracheid specific surface and, to a marginally significant extent, wood brightness. The surface area of fibres is well known to be a function of fibre coarseness (Rennel 1969, Seth 1990), however this more fundamental tracheid property added no extra significant information than coarseness.

The models in Table (4.4) greatly simplify the interaction between brightness and opacity in the papermaking process, both of which are functions of the light absorption (*AB*) and scattering properties (*SC*) of the pulp it is made from. Both *AB* and *SC* contribute to opacity, however it is the ratio of *AB*/*SC* that determines pulp brightness (N.Collins, pers. com.). For most purposes, the ideal paper should be high in opacity and brightness. This means that *SC* should be as high as possible and *AB* should be at a value which is high enough to provide a good opacifying contribution but low enough to keep *AB*/*SC* at a sufficiently low level for high brightness. It should be noted that brightness and opacity are measured at different wavelength regions and that precise descriptions of interrelationships require calculation of scattering and absorption in each of the two regions. Hence a more accurate description of the impact that the selection traits have on the trade-off between brightness and opacity would require calculation of both *SC* and *AB* in each of the two regions.

The total cost of pulping model (Equation 4.1) can hence be explained in terms of tracheid length, wood density, wood brightness and tracheid coarseness (Table 4.4). It is interesting to note that the more fundamental tracheid properties studied were no better predictors of the pulp traits, than the easier to measure wood traits examined.

We expect the wide variation of wood samples used in this study to result in robust relationships between respective traits, consistent across a range of environments and ages. However, this also presents a limitation to the current analysis, in that no distinction is made between the three different samples used. Wood traits in radiata pine are known to vary greatly with tree age and ring position (e.g. Nicholls 1965, Burdon *et al.* 1992, Cown *et al.* 1992, Shelbourne *et al.* 1997). In addition, the empirical relationships developed between wood traits and paper quality traits will be influenced by the variance of the wood traits, which is itself a function of the specific sample used. It is also logical, that pulp freeness would be affected by some of the basic wood properties being analysed. Hence, the method of adjusting to a constant 100 CSF using regression interpolation may in fact mask some of the impact of the biological traits under investigation.

4.5.3 Application of the Model

Assuming the wood trait mean values in Table (4.1) are the current overall mean values of wood material entering the TMP system, the total cost of pulping (see also Figure 3.2) would be:

$$C_T = C_c + C_r + (C_b + C_f + C_k)$$

where: C_c = \$20 per odt.P

$C_r = (E_m) * c_r$ (from Equation 4.4)

= {3748-(1.29*length*density)} * c_r(from Table 4.4)

= \$91.87 per odt.P (assuming c_r = \$0.04 /kWhr)

Similarly, C_b equals \$47.22, $C_f$equals \$47.24, and C_k equals \$35.43 per odt.P

$\therefore C_T$ = \$241.77 per odt.P

If, for example, we were able to change the overall trait means of wood material used for thermo-mechanical pulping (Table 4.1) through selective breeding, say increasing tracheid length by 0.3 mm, basic wood density by 12 $kg.m^{-3}$, and wood brightness by 3%, but decreasing coarseness by 0.04 $mg.m^{-1}$ the total cost of pulping the improved material would be:

$$C_T = C_c + C_r + (C_b + C_f + C_k)$$

= 20.00 + 83.17 + (31.96 + 45.01 + 23.96)

= \$204.10 per odt.P.

This new material then, has the potential to save around $37.67 per odt.P. For an international scale TMP mill producing, say 200,000 tonnes of pulp per year, savings of approximately 7.5 million dollars per year would be expected.

4.5.4 Economic Weights

Using the models and relationships developed, the economic importance of each wood trait was established (Figure 4.2). The costs per unit of each commodity, on which this analysis was derived, were based on international long-term market values (P. Sylvester, pers. com.). Total pulping costs will obviously change depending on variations in these commodity costs. For example, power costs may range internationally from 0.01$/kWh to over 0.07$/kWh depending on the region where the TMP mill is situated. Likewise, the costs of bleaching chemicals, artificial fillers and kraft pulp depend on the supply and demand for each, which vary over time.

Figure 4.2- The impact of tracheid length (————), basic wood density (·····), tracheid coarseness (— - — - —) and wood brightness (- - - - - - -) on the total cost of pulping ($/odt.P). Observable ranges for each selection trait are +/- 2 standard deviations either side of each trait mean, as shown in Table (4.1).

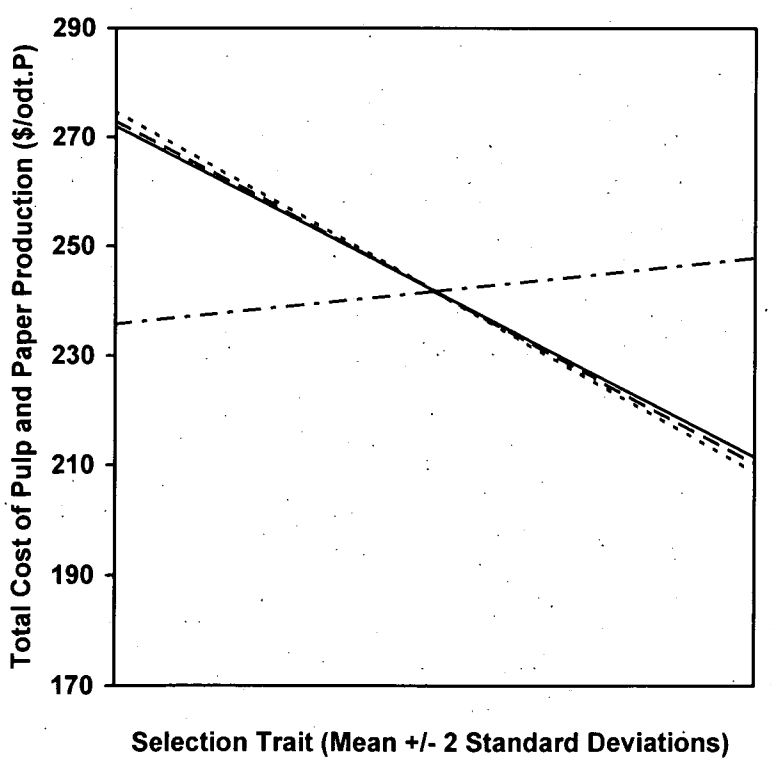


Table (4.5) presents the economic weights for each wood trait, given as marginal changes in C_T from changes in one unit, or in the case of relative weights, one phenotypic standard deviation, of tracheid length, wood density, wood brightness or tracheid coarseness. Tracheid length, wood density and wood brightness are, in relative terms, of equivalent importance, being around five times more important than tracheid coarseness, when aiming to minimise the total cost of pulping (Table 4.5). The economic weight for tracheid coarseness was negative indicating that increasing coarseness will result in higher pulping costs, which is in opposition to our current objective. The relative impact of each wood trait on the total costs of pulping is shown diagrammatically in Figure (4.2) for a range of two standard deviations either side of each wood trait mean (see Table 4.1). Although not all of the observable variation shown in Figure (4.2) can be exploited through genetic improvement or silviculture, it provides a relative indication of the amount of variation available. These results are in contrast with a similar study conducted for a normal newsprint grade of paper (Chambers *et al.* 1997- "Chapter 5"), where tracheid length and wood density were up to twice as important as wood brightness with a similar cost minimisation objective in mind.

Table 4.5- Absolute economic weights ($W_{absolute}$) for tracheid length, wood density, wood brightness and tracheid coarseness: mean, standard deviation, and coefficient of variation estimated for input parameter range (see text). All values represent gains in reducing the total cost of pulping (C_T) in $/odt.P. Relative economic weights ($W_{relative}$) represent gains in reducing one unit of phenotypic standard deviation. Negative values represent an increase in C_T.

Wood Trait	$W_{absolute}$			$W_{relative}$
	mean	*s.d.*	CV	
Tracheid Length (mm)	50.35	7.23	14.4%	14.90
Wood Density (kg.m^{-3})	0.37	0.06	15.8%	16.94
Wood Brightness (%)	5.09	0.44	18.5%	15.63
Coarseness (mg.m^{-1})	-67.69	14.19	-24.0%	3.05

Standard errors for economic weights (Table 4.5) were estimated using Monte-Carlo simulation using @RISK software (Palisade 1997). All model parameters, commodity costs and biological wood trait values were allowed to vary. Model parameters were varied by twice their standard error of predictions assuming a normal probability distribution. In general, the true value of a regression coefficient is likely to lie within this range of two standard errors either side of the estimated mean value (Draper and Smith 1981). Commodity costs were varied by +/-20% with an assumed triangular distribution, while wood traits were varied by twice their observable standard deviations assuming a normal probability

distribution. Monte-Carlo simulation was used to generate 10,000 production system input parameter sets, and for each parameter set economic weights were estimated. It must be noted that the standard deviations and coefficients of variation for derived economic weights in Table (4.5) are directly proportional to the allowable range of variation used in the Monte-Carlo simulation.

Moav (1973) estimated the economic weight of genetic improvement for different perspectives concluding that the relative weight of trait improvement may change depending upon the perspective. The basic premise used in this paper, is that cost is the only variable worth modeling. However, of equally relevant importance is product value, for example when improvements to high brightness newsprint enable it to be sold as a higher grade of paper for higher return. Consideration of product value in addition to cost may result in more broadly relevant economic weightings. Anthony and Reece (1989), in discussing the application of economic indicators to long-term investment decision analysis, conclude that when choosing between investment options, the Profitability index method is the best indicator. Profitability index is the ratio of the present value of profit (being total returns minus total costs) and the present value of total costs (Anthony and Reece 1989). Such an analysis was not conducted in the current chapter.

4.5.5 Sensitivity Analysis

Rank order correlation (Palisade 1997) was utilised to determine the production system and trait-change input parameters having the greatest influence on the established economic weights. The three most correlated input parameters with the derived economic weight of each wood trait are presented in Table (4.6). The rank order correlation (Table 4.6) represents the strength of the relationship between the estimated economic weight and the production system input parameter (including all model parameters, commodity costs and biological wood trait values) given the assumed allowable variation in input parameters (see economic weights section). These correlations are indicators of the input parameters that could be further verified to increase the reliability of the economic weight for each trait. For example, the economic weight for wood brightness shows a strong relationship with the effect of a β coefficient (0.52) in the model relating pulp handsheet brightness to wood brightness (r=-0.62): refer to Table (4.4) for the model. Hence the first parameter that should be verified to confirm the estimated economic weight for wood brightness, once more data becomes available, is this input. The impact of the most correlated input parameter for each wood trait on the respective economic weights is shown in Figure (4.3).

Table 4.6- Sensitivity analysis: Rank Order Correlation between Absolute Economic Weight and the three most correlated production system inputs (including model parameters and commodity costs), by trait. Model parameters are in bold and slightly larger text in their respective equations from Tables (4.2) and (4.4).

Economic weight	Correlated production system input parameter	Rank Order Correlation
Tracheid Length	TE_m = -1.8+(**1.33****length*)+(0.015**density*)	0.46
	Cost of **Power** ($/Kwh)	0.41
	Cost of **Kraft** Pulp ($/odt)	0.38
Wood Density	TE_m = -1.8+(1.33**length*)+(**0.015****density*)	0.51
	Cost of **Kraft** Pulp ($/odt)	0.45
	k = {**2.5***(9.0-TE_m)}+{0.27*(42.0-TN_m)}+{0.20*f}	0.38
Wood Brightness	PB_m = 37.9+(**0.52****bright*)	-0.62
	p = (80-PB_m)/**4.10**	-0.50
	Cost of H_2O_2 ($/t)	0.16
Tracheid Coarseness	OP_m = 68.2+{**0.03***669-(357**coarse*)}	-0.56
	f = (94-OP_m)/**1.25**	-0.43
	Cost of **Filler** ($/odt)	-0.30

4.5.6 Reliability of Results

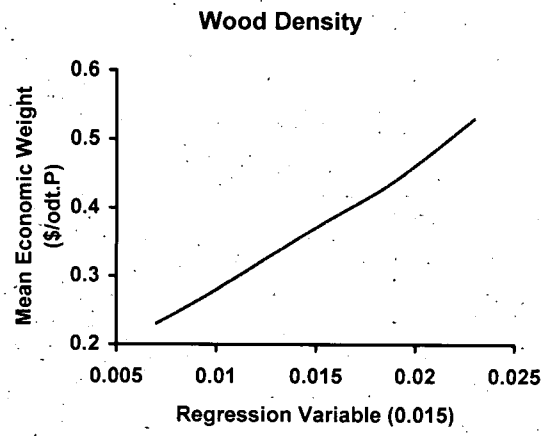
The most important traits for breeding to reduce the cost of TMP and high brightness production were identified as wood density, wood brightness and tracheid length (Table 4.5). Using sensitivity analysis the key assumptions underlying this conclusion were identified (Table 4.6). However, the model described has not been investigated beyond the observational range of wood traits as listed in Table (4.1) and the range of pulp and quality traits as listed in Table (4.4). In addition, a number of the relationships used were assumed to be linear, which was a valid assumption only given the fairly limited range of the response curve in each case. Nevertheless given the range of the defined parameters, Figure (4.3) shows only limited variation in economic weights due to variation in the most correlated input parameters (which included commodity costs and regression variables) for each wood trait within the specified range. Ultimately, as a model for tree breeding purposes we need to be sure that, when combined with genetic information for each trait, the same trees would be selected given the variation in estimated economic weights. However, as Greaves (1999) notes in the application of economic weights to breeding, gain from selection is, on the whole, more sensitive to variation in genetic parameters than to variation in economic weights.

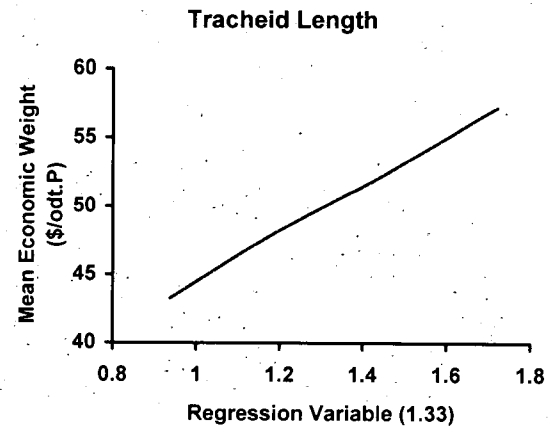
4.5.7 Implications for tree breeders

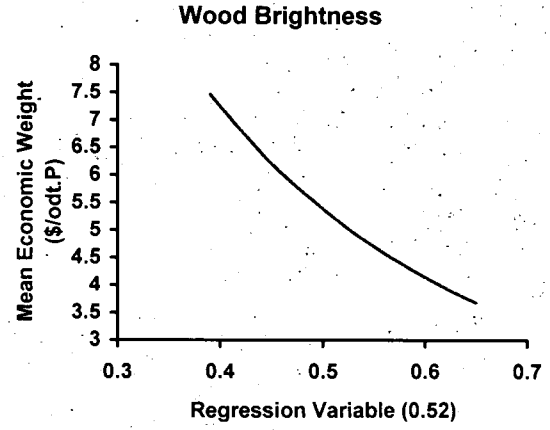
This study centres on just one part of an overall process to develop a breeding objective for thermo-mechanical pulping using radiata pine as a wood source. The full impact of including wood traits in a breeding objective also relies on the expenses involved with the establishment, growing and harvesting of a pine plantation and transportation of roundwood to a TMP mill. For example wood density will affect the transport costs of pine roundwood from the harvested plantation to the TMP mill (Greaves *et al.* 1997), whereas tracheid length, tracheid coarseness and wood brightness do not. By increasing wood density, more pulp can be produced per odt of delivered roundwood, and thus the total production costs will be reduced. The effect of other production traits like tree growth and survival, which do not impact on the pulping and paper quality costs examined in this paper, have an important impact on costs in other components of the production system as a whole (see Chapters 12 and 13, Greaves *et al.* 1997).

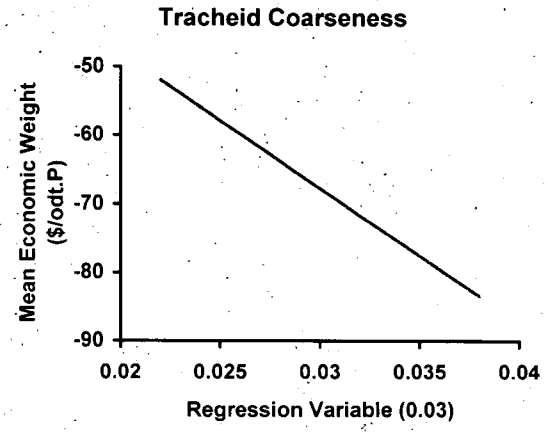
In addition, the importance of each selection trait is dependent on the degree of exploitable genetic variation and the accuracy of predicting the genotypic value (the square root of heritability in the simplest case of phenotypic selection) which differ among the traits examined, and the genetic relatedness between the traits examined. Nevertheless, the results clearly suggest that major reductions in the total pulp and paper mill costs are attainable by increasing the tracheid length, wood density and wood brightness of material entering the pulp and paper production process, and to a lesser extent by reducing trachied coarseness. As the grade of paper produced from thermo-mechanical pulp increases, it may also be expected that the importance of improving coarseness will also increase, due to the costs of adding increased amounts of clay (up to 34% for Surface Coated Paper; Ionides and Moller, 1997) and the calendering involved.

Figure 4.3- Sensitivity of the estimated economic weights for each wood trait for the most correlated input parameter from Table (3.6). Input parameters were varied by twice their respective standard deviations, assuming a normal distribution (@RISK, Palisade 1997). Standard deviations for each parameter were given by the *PROC REG* procedure in SAS (SAS, 1996).









4.6 Conclusion

The total operational costs of converting green radiata pine roundwood to a high mechanical grade paper using the thermo-mechanical pulping process were shown to decrease with increasing tracheid length, wood density and wood brightness and decreasing tracheid coarseness. Tracheid length, wood density and wood brightness have an almost equivalent impact on total mill costs, being around five times more important than tracheid coarseness. Tracheid length and wood density have a major influence in determining the energy required to refine TMP to a particular freeness, and in determining the subsequent strength properties of the paper product, while wood brightness influences the amount of bleach required in the process. It is expected, that tracheid coarseness, which also affects the optical properties of paper would become even more important as the grade of paper quality produced increases.

Chapter 5

The impact of wood selection traits on a thermomechanical pulping system using radiata pine to - produce newsprint

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Chapter 6

A review of the contemporary theory in the definition of breeding objectives

6.1 Introduction

The initial step in the design of a breeding program is to decide on that program's objectives (Goddard 1998). The idea of defining a breeding objective is not special, indeed all breeding programs have objectives even if these are not quantified and are present only in the minds of the forest grower. However, the importance of a quantifiable economic objective in tree breeding cannot be overstated (Woolaston and Jarvis 1995). As put by Amer (1994), the correct definition of a breeding objective 'will result in more return from breeding with no extra breeding effort'. Alternatively, defining inappropriate objectives causes too much selection pressure to be applied to the wrong traits, leading to sub-optimal gains (James 1982). Indeed inappropriate objectives have been suggested as the largest inefficiency of breeding programs to date (Goddard 1998).

Since Hazel (1943) introduced this total merit index, the methodology for defining breeding objectives has been debated (Amer 1994, Goddard 1998). This debate has included the definition of profit, the unit for which it was calculated, the perspective from which profit was viewed (producer or consumer), the traits to be included, the use of discount rates, bioeconomic models versus the estimation of economic weights by multiple regression, and economic versus biological objectives (Goddard 1998). Fortunately the conjecture surrounding most of these issues has been satisfied with a general consensus reached in each case. The term 'economic value' as originally described by Hazel (1943), implies a basis for economic theory in formulating the breeding objective. However, as discussed by Amer (1994), developments in the theory of estimating economic values reported in the literature (mostly from an animal breeding perspective, e.g. Dickerson 1970, Brascamp *et al.*

1985, Smith *et al.* 1986) conflict with the rational and empirical basis for economic theory of firms (McArthur 1987, Groen 1989, Amer and Fox 1992). Two main issues can be identified:

- the need to account for reoptimisation of the production enterprise system in production input use, and output levels, in response to genetic changes (Amer 1994); and
- accounting for changes in input or output prices which can result when genetic change occurs across a large proportion of a competitive industry (Amer and Fox 1994).

From the context of forestry, the breeding objective may be defined generally as the development of plantation trees which will ensure that profit is as high as possible under future commercial conditions of production. This general definition can then be transferred to a given enterprise objective for a given population by:

- deciding which traits to include in the objective definition; and
- weighting the traits with economic coefficients or values according to Hazel (1943).

Although a wealth of published work exists for the development of animal breeding objectives, there is still relatively little reported work in the area of tree breeding objectives. Chollet and Roman-Amat (1986) derived a breeding objective for *Pinus pinaster* grown for veneer based on growth rate and stem sweep. Borralho *et al* (1993) developed an objective for *Eucalyptus globulus* ssp. *globulus* grown for kraft pulp production based on growth rate, basic density and kraft pulp yield. Greaves *et al.* (1997) applied the methodology of Borralho *et al.* (1993) to *Eucalyptus nitens* including a stem form trait and a refined kraft pulping cost model. Chambers *et al.* (1997) (Chapter 5) and Chambers and Borralho (1999) (Chapter 4) developed relationships relating tracheid length, coarseness, basic density and wood brightness to the cost of thermo-mechanical pulping and the manufacture of newsprint and a high brightness newsprint respectively. Shelbourne *et al.* (1997) also discusses the formal method of Ponzoni (1986) in relation to the development of breeding objective functions for radiata pine. He identifies a large number of traits with potential as breeding objective traits for different end product usage.

Breeding objectives are not an end in themselves but are part of a decision-making process (Goddard 1998). Important decisions that make use of a breeding objective include:

- the choice of individual trees as parents; and

- the evaluation of investment in breeding programs.

The first decision requires that the breeding objective must lead to selection criteria, while the second requires that the breeding objective must be related to predicted genetic changes. It would be greatly desirable that the same objective be used for both decisions (Goddard 1998). To accommodate this, the breeding objective must be written in terms of traits that apply to individuals or groups of individuals and in which genetic changes can be predicted. Goddard (1998) characterise the use of breeding objectives by a common scheme:

- for alternative decisions (e.g. alternative choice of parents), the genetic merit of the offspring and possibly later generations of descendants is predicted for traits in the breeding objective. This initial step concerns the establishment of selection criteria, the estimation of breeding values and the prediction of genetic response.

- a profit function is used to combine the genetic merits of various traits into a single value (e.g. profit) so that the decision with the greatest value of the objective can be identified. This second step is solely concerned with the calculation of the breeding objective function.

This chapter deals briefly with the first step (i.e. prediction of breeding values) but concentrates primarily on the second step (i.e. the definition of the breeding objective function). For the second step, the chapter attempts to outline the current consensus for a number of debated issues, without delving too deeply into documenting the history surrounding these debates. It outlines the method by which some of the issues have been resolved and comments on others that are still under debate or identified by Goddard (1998) as receiving little consideration in the past.

6.2 Prediction of Breeding Values

6.2.1 The Infinitesimal Model

The prediction of breeding values constitutes an integral part of forest tree breeding programs for genetic improvement (White and Hodge 1989). A crucial factor in the prediction of breeding values, at least with any degree of accuracy, is the availability of records. From basic quantitative genetics (see Turner and Young 1969, Bulmer 1980, Becker 1984, Nicholas 1993, Falconer and Mackay 1996,

Lynch and Walsh 1998), every phenotypic observation on a tree is determined by environmental and genetic factors and is defined by the following model:

$$y_{ij} = \mu_i + g_i + e_{ij} \qquad (6.1)$$

where:

- y_{ij} is the record j of the i^{th} tree;
- μ_i refers to the identifiable non-random (fixed) environmental effects of the i^{th} tree;
- g_i is the sum of the additive (g_a), dominance (g_d) and epistatic (g_e) genetic values of the genotype of tree i; and
- e_{ij} is the sum of random environmental effects affecting tree i.

The additive genetic value in the g term from Equation (6.1) represents the average additive effects of genes an individual tree receives from both parents and is also termed the breeding value of that individual. Since the additive genetic value is a function of the genes transmitted from parents to progeny, it has traditionally been the sole component that has been selected for in breeding. In the majority of cases, dominance and epistasis, which represent intralocus and interlocus interactions respectively, are assumed to be of little significance and are included in the e_{ij} term of the model (White and Hodge 1989, Mrode 1996). However, dominance and epistasis are increasingly being exploited in breeding programmes today as cloning for tree crops becomes feasible commercially. It is usually assumed that y follows a multivariate normal distribution, implying that traits are determined by an infinite of additive genes of infinitesimal effect at unlinked loci, or what is commonly referred to as the "infinitesimal model" (Fischer 1918, Turner and Young 1969, Bulmer 1980, Becker 1984). Also it is assumed that the additive genetic variance, $var(g_{ai})$, and the unexplained residual variance $var(e_{ij})$, are known, or at least that their proportionality is known (Mrode 1996), and that their is no correlation between g_{ai} and e_{ij} ($cov(g_{ai}, e_{ij}) = 0$) and no correlation among parents ($cov(e_{ij}, e_{ik}) = 0$). Also, μ, which usually symbolises the mean performance of trees in any given group (e.g. trees within the same block) is assumed to be known.

From Equation 6.1, the problem of predicting a breeding value reduces to that of adjusting phenotypic observations for identifiable non-random environmental effects and appropriately weighting the records of trees and their available relatives (Mrode 1996). Following the earlier explanation, if a_i is the breeding value of tree i, then:

$$a_i = g_{ai} = \frac{1}{2}a_{mum} + \frac{1}{2}a_{dad} + m_i \qquad (6.2)$$

where:

- a_{mum} and a_{dad} are the breeding values of the parental trees; and
- m_i is the deviation of the breeding value of tree i from the average breeding value for both parents (Mendelian sampling).

The sampling nature of inheritance implies that each parent passes only a sample half of its genes to its progeny, and hence there is genetic variation between offspring of the same parent trees as all offspring do not receive exactly the same genes. Mrode (1996) regards Mendelian sampling as "the deviation of the average effects of additive genes an individual receives from both parents from the average effects of genes common to all offspring of the same parents".

The accurate prediction of breeding values constitutes a critical component of any tree breeding program, since genetic improvement through selection depends on correctly identifying individual trees with outstanding qualities (highest true breeding value). The method employed for the prediction of breeding values depend on the type and amount of information available on candidates for selection.

6.2.2 Single Record Scenario – Phenotypic Selection

For the simplest case, when dealing with a single trait and when one phenotypic record is the only available information on each tree, the estimated breeding value ($\hat{a}_i$) for tree i can be calculated following:

$$\hat{a}_i = b(y_i - \mu) \qquad (6.3)$$

where:

- b is the regression of the true breeding value on the phenotypic performance; and
- μ is the mean performance of trees in the same grouping and is assumed to be known.

Hence:

$$b = \frac{\text{cov}(a, y)}{\text{var}(y)} = \frac{\text{cov}(a, a+e)}{\text{var}(y)} = \frac{\sigma_a^2}{\sigma_y^2} = h^2 \qquad (6.4)$$

The breeding value prediction then is simply the adjusted record multiplied by the heritability (h^2). The accuracy of prediction is estimated as the correlation between the selection criterion, in this case the phenotypic value, and the true breeding value. This provides a means of evaluating different selection criteria because the higher the correlation the better the criterion as a predictor of the breeding value (Mrode 1996). With a single record per tree the accuracy of selection ($r_{a,y}$) is:

$$r_{a,y} = \frac{\mathrm{cov}(a,y)}{(\sigma_a \sigma_y)} = \frac{\sigma_a^2}{(\sigma_a \sigma_y)} = h \qquad (6.5)$$

The expected response (R) to selection on the basis of a single record per tree (Falconer and Mackay 1996) is:

$$R = i r_{a,y}^2 \sigma_y = i h^2 \sigma_y \qquad (6.6)$$

where:

- i is the intensity of selection and refers to the superiority of selected individuals above the population average, expressed in units of phenotypic standard deviation.

6.2.3 Correlated Response

In the previous section, the response to selection on a single trait with a single phenotypic record was shown to be dependent on the ratio of genetic to phenotypic variance (heritability) for that trait (Equation 6.6). When several traits are measured on each individual however, phenotypic and genetic covariances among the traits need to be computed. If the traits have a non-zero genetic correlation, then direct selection on one will lead to a genetic change on the other. This change is known widely as the "correlated response". As such, the breeding value of one trait may be predicted from the observation on another trait if the traits are genetically correlated, If y is the observation of individual i from one trait, its breeding value for another trait x is:

$$\hat{a}_{ix} = b(y_i - \mu) \qquad (6.7)$$

with

$$b = \frac{\mathrm{cov}(a_x, \textbf{measurement } y)}{\textbf{var(measurement } y)} \qquad (6.8)$$

The genetic correlation between traits x and y (r_{axy}) is:

$r_{axy} = \frac{\text{cov}(a_x, a_y)}{\sigma_{ax}.\sigma_{ay}}$ (following Falconer and Mackay 1996).

Therefore:

$$\text{cov}(a_x, a_y) = r_{axy}\sigma_{ax}\sigma_{ay} \quad (6.9)$$

Substituting equation (6.9) into equation (6.8):

$$b = \frac{r_{axy}\sigma_{ay}\sigma_{ax}}{\sigma_y^2} \quad (6.10)$$

If the additive genetic standard deviations for x and y in equation (6.10) are expressed as the product of the square root of their individual heritabilities and phenotypic variances, then the weighting factor, b, depends on the genetic correlation between the two traits, their heritabilities and phenotypic standard deviations:

$$b = \frac{r_{axy}\sigma_y\sigma_x h_x h_y}{\sigma_y^2} = \frac{r_{axy}h_x h_y\sigma_x}{\sigma_y} \quad (6.11)$$

The accuracy of the predicted breeding value ($r_{ax,y}$) depends on the genetic correlation between the two traits and the heritability of the recorded trait:

$$r_{ax,y} = \frac{\text{cov}(a_x, \textbf{measurement } y)}{\sigma_{ax}\sigma_y} = \frac{r_{axy}\sigma_{ay}\sigma_{ax}}{\sigma_{ax}\sigma_y} = r_{axy}h_y \quad (6.12)$$

The correlated response ($R_{x/y}$) in trait x as a result of direct selection on y (Falconer and Mackay 1996) is:

$$R_{x/y} = ih_x h_y r_{axy}\sigma_y \quad (6.13)$$

6.2.4 Selection Index

Hazel and Lush (1942) and Smith (1936) independently proposed the idea of a linear function of recorded traits, or selection index, as the basis of selection. This selection index is a method for estimating the breeding value of an individual combining all information available of an individual and its relatives. It is the best linear prediction of an individual breeding value. The numerical value obtained for each tree is referred to as the index (I) and it is the basis on which trees are ranked for selection. Suppose y_1, y_2 and y_3 are phenotypic values for three characteristics of tree i, the index for this tree would be:

$$I_i = \hat{a}_i = b_1(y_1 - \mu) + b_2(y_1 - \mu) + b_3(y_1 - \mu) \qquad (6.14)$$

where:

- b_1, b_2 and b_3 are the factors by which each measurement is weighted.

The determination of the appropriate weights (b) for the several sources of information is the main concern of the selection index procedure. The index defined in Equation 6.14 may be thought of as an estimate of the true breeding value of tree i.

The major properties of the selection index (following Van Vleck 1993) are:

1. It minimises the average square prediction error, i.e. minimises the average of all $(a_i - \hat{a}_i)^2$.

2. It maximises the correlation between the true breeding value and the index ($r_{a,\hat{a}}$). This correlation is referred to as the accuracy of prediction.

3. The probability of correctly ranking pairs of trees on their breeding value is maximised.

The b values in Equation (6.14) found by minimising $(a-I)^2$, which is equivalent to maximising $r_{a,I}$. This is the same procedure as that employed in obtaining the regression coefficients in multiple linear regression (White and Hodge 1989, Mrode 1996). Hence the b values could be regarded as partial regression coefficients of the individual tree's breeding value on each measurement. The minimisation procedure results in a set of equations which require solving to obtain the b values. For example, the set of equations to be solved for b from Equation (6.14) is:

$$\begin{aligned} b_1 p_{11} + b_2 p_{12} + \ldots\ldots + b_m p_{1m} &= g_{11} \\ b_1 p_{21} + b_2 p_{22} + \ldots\ldots + b_m p_{2m} &= g_{12} \\ \vdots \qquad\qquad & \qquad \vdots \\ b_1 p_{m1} + b_2 p_{m2} + \ldots\ldots + b_m p_{mm} &= g_{1m} \end{aligned} \qquad (6.15)$$

where:

- p_{ii} and g_{ii} are the phenotypic and genetic variances respectively for individual or trait i; and

- p_{ij} and g_{ij} are the phenotypic and genetic covariances respectively between individuals or traits i and j.

In matrix notation, Equation (6.15) may be expressed as:

$$\mathbf{Pb} = \mathbf{G} \tag{6.16}$$

and thus:

$$\mathbf{b} = \mathbf{P}^{-1}\mathbf{G} \tag{6.17}$$

where:

- **P** is the variance – covariance matrix for phenotypic observations; and
- **G** is the covariance matrix between observations and the breeding value to be predicted.

Therefore the selection index equation is:

$$I = \hat{a} = \mathbf{P}^{-1}\mathbf{G}(y - \mu) = \mathbf{b}'(y - \mu) \tag{6.18}$$

where:

- μ refers to estimates of environmental influences on observations, assumed to be known without error.

6.2.5 Accuracy of the Selection Index

The accuracy of the selection index is established essentially the same way as for the simple single trait case previously, in that it is the correlation between the true breeding value and the estimated value (the index). Thus, the higher the correlation, the better the index as a predictor of breeding value. This correlation provides a means of evaluating different indices based on different observations (Mrode 1996), to establish for example, whether a particular observation is worth including in an index or not. From the previous definition above:

$$r_{a,I} = \frac{\mathrm{cov}(a, I)}{\sigma_a \sigma_I} \tag{6.19}$$

and

$$\sigma_I^2 = \sum_{i=1}^{m} b_i^2 p_{ii} + \left(\sum_{i=1}^{m} \sum_{j=1}^{m} b_i b_j p_{ij}; \quad i \neq j \right) \tag{6.20}$$

where:

- m is the number of traits or individual trees in the index.

In matrix notation:

$$\sigma_I^2 = \mathbf{b}'\mathbf{P}\mathbf{b} \tag{6.21}$$

and substituting for the unknown vector **b**:

$$\sigma_I^2 = \mathbf{G}'\mathbf{P}^{-1}\mathbf{G} \tag{6.22}$$

The covariance between the true breeding value for trait or individual i and the index is:

$$\text{cov}(a, I) = \sum_{j=1}^{m} b_j g_{ij} \tag{6.23}$$

where:

- g_{ij} is the genetic covariance between traits or individuals i and j, and m is the number of traits or individuals in the index.

In matrix notation:

$$\text{cov}(a_i, I) = \mathbf{b}'\mathbf{G} \tag{6.24}$$

and substituting for the unknown vector **b**:

$$\text{cov}(a_i, I) = \mathbf{G}'\mathbf{P}^{-1}\mathbf{G} = \sigma_I^2 \tag{6.25}$$

Hence, as previously described for the simple single record scenario, the regression of breeding value on predicted breeding value is unity. Therefore:

$$r_{a,I} = \frac{\sigma_I^2}{\sigma_a \sigma_I} = \frac{\sigma_I}{\sigma_a} = \sqrt{\frac{\sum_{j=1}^{m} b_j g_{ij}}{\sigma_a^2}} \tag{6.26}$$

Response to selection on the basis of an index (White and Hodge 1989, Cotterill and Dean 1990) is:

$$R = i r_{a,I} \sigma_a = i \sigma_I \tag{6.27}$$

6.2.6 Introduction to Best Linear Unbiased Prediction

The classical selection index outlined in Section (6.2.4), assumes equal amounts and quality of data available for all candidates. Further, the classical index can

realistically only incorporate information from direct relatives, and the fixed effects are predetermined often using only ordinary least-squares methodology (Kerr 1998). In field populations however, data are often unbalanced; individuals will have differing levels and sources of data (Borralho 1995). As a method of combined index selection, selection on best linear unbiased predictors (BLUP) is optimal (Goffinet 1983) because in effect a customised index is created for each individual (Kerr 1998). Because all relationships between individuals are included, any bias due to genetic or any known environmental trend is removed because solutions to environmental effects are computed simulateously with the genetic effects (Mrode 1996, Kerr 1998). More optimal is selection on multiple traits using multivariate BLUP, as bias due to selection on a correlated trait can be avoided (Borralho 1995, Kerr 1998). BLUPs are estimated by a variation of the least-squares method of estimation, initially suggested by Henderson (1975) and described by many authors including Nicholas (1987), Borralho (1995) and Mrode (1996). It is beyond the scope of this thesis, however, to present the theoretical background for the estimation of BLUPs from mixed model equations.

BLUP is an integral component of national genetic evaluation strategies for animal breeding industries (eg. Villanueva *et al.* 1993) and more recently for tree breeding within Australia (see Jarvis *et al.* 1995, Borralho 1995). However, deterministic prediction of genetic gain from selection on breeding values derived using BLUP is not straightforward because the amounts and types of information used to predict breeding values will differ between individuals (Kerr 1998). Wray and Hill (1989) were able to formulate an index that was reasonably able to predict rates of response from single trait BLUP selection. In a similar manner, Villanueva *et al.* (1993) formulated equations for the multivariate case. Chapter 12 presents BLUPs estimated for growth and survival traits in *Eucalyptus nitens* across two sites in central, southern Tasmania.

6.3 Prediction of Aggregate Genotype

The works of Hazel and Lush (1942) and Smith (1936) led to the land-mark paper of Hazel (1943), where the key concept of aggregate genotype, or breeding objective was formulated. The aim of this concept was not just to predict the breeding value of a single trait but to predict that of a composite of several traits evaluated in economic terms. Hazel (1943) defined an objective that was a linear combination of traits in which the coefficient of each trait was its effect on profit when all other traits were held constant. This coefficient may be defined as the economic value, or more commonly the economic weight of each trait toward the total profitability of

the objective. Thus the aggregate economic value of a genotype (H) as defined by Hazel (1943) can be approximated following:

$$H = w_1 a_1 + w_2 a_2 + ... + w_n a_n \quad (6.28)$$

where:

- H is the aggregate value of the genotype (breeding objective)
- a_1 to a_n are the breeding values of the i^{th} trait; and
- w_1 to w_n are the economic coefficients (weights).

The construction of an index to predict or improve H is based on the same principles discussed previously for the selection index except that it includes the relative economic weight for each trait. Thus:

$$I = \mathbf{P}^{-1}\mathbf{G}\mathbf{w}(y - \mu) \quad (6.29)$$

where:

- **w** is the vector of economic weights and all other terms are described previously in Equation (6.28).

The equations to be solved to get the weights (b values) to be used in the index are:

$$\begin{aligned} b_1 p_{11} + b_2 p_{12} + ... + b_m p_{1m} &= w_1 g_{11} + w_2 g_{12} + ... + w_m g_{1m} \\ b_1 p_{21} + b_2 p_{22} + ... + b_m p_{2m} &= w_1 g_{21} + w_2 g_{22} + ... + w_m g_{2m} \\ \vdots \qquad\qquad & \qquad \vdots \qquad\qquad \vdots \\ b_1 p_{m1} + b_2 p_{m2} + ... + b_m p_{mm} &= w_1 g_{m1} + w_2 g_{m2} + ... + w_m g_{mm} \end{aligned} \quad (6.30)$$

In matrix notation these equations are:

$$\mathbf{Pb} = \mathbf{Gw} \quad (6.31)$$

and thus

$$\mathbf{b} = \mathbf{P}^{-1}\mathbf{Gw} \quad (6.32)$$

An important concept (discussed in detail later in this chapter) is the possibility for there to be some traits in the index which are not in the aggregate breeding value but which may be correlated with other traits in H. Conversely, some traits in the aggregate breeding value may be difficult to measure or occur later in life and may therefore not be in the index. For example, it is a common theme in forest tree improvement to base selections for harvestable volume per hectare at rotation age

on stem diameter at an early, juvenile age. The accuracy of the index under these circumstances relies heavily on the juvenile-mature correlations between what we are selecting for and the breeding objective trait we are wishing to improve. Hence volume per hectare at rotation age (say 25 years for a sawlog rotation) is replaced in the index by the correlated trait diameter at four years, which is far easier to measure, and measured earlier in life. Consequently, the vector of economic weights will not necessarily be of the same dimension as traits in the index. Each trait in the index is weighted by the economic weight relevant to the breeding value of the trait it is predicting in the aggregate breeding value.

The index calculated using Equation (6.29) implies that the same economic weights are applied to the traits in the breeding objective across the whole population. A change in the economic weights for just one of these traits would require that the index be recalculated. An alternative formulation as presented by Mrode (1996) for Equation (6.29) involves calculating a sub-index for each trait in H without the economic weights. The final index, as shown below (Equation 6.33) is obtained by summing the sub-indices for each trait weighted by their respective economic weights. Thus:

$$I = \sum_{i=1}^{m} I_i w_i \qquad (6.33)$$

where:

- $I_i = \mathbf{P}^{-1}\mathbf{G}_i(\boldsymbol{y}-\boldsymbol{\mu})$, the sub-index for trait i in H; and
- w_i is the economic weight for trait i.

Using Equation (6.33), a change in the economic weights of any of the traits in the index can easily be implemented without recalculating the index (Mrode 1996).

This section has defined the aggregate genotype or breeding objective as outlined by Hazel (1943). However, although an important ground-breaking work at the time, the limitations of Hazel's method, especially in the context of breeding objective work undertaken today, should be discussed. Firstly, the selection index, as formulated by Hazel (1943) only solves the case where the economic values are a linear function of the trait values. This may be a reasonable assumption only when looking at relatively narrow regions of the response curve of each trait to profitability. Secondly, selection index theory assumes that the economic weights are known *a priori* (Weller 1994). Not only is this unlikely, but economic weights tend to change over time and region. Finally, the selection index only provides relative weights between the traits in question, and does not answer the question of whether breeding is economically justified (Weller 1994).

6.4 Early Attempts in Defining Aggregate Genotype

The majority of the theoretical basis for tree breeding derives from quantitative genetics as it has been applied in animal breeding (Shelbourne *et al.* 1997). Following this model Cotterill and Dean (1990) presented the concept of Hazel's (1943) "aggregate genotype" from a tree breeding perspective. Many of the earlier attempts in tree breeding at defining an objective similar to Hazels may have been less than optimal due to the arbitrary allocation of the economic coefficients. Coefficients were generally derived purely on a subjective basis and hence had no real basis on the profitability or economic value of the traits. This may have been due to the perceived difficulty in deciding on the economic weights (w). In Hazel's formulation, these should reflect net economic impact- the "amount by which profit may be expected to increase for each unit of improvement in each trait". In other words, they are not simply prices per unit of product, but should reflect changes in profit or income when all other traits in the breeding objective are held constant.

Cotterill and Dean (1990) based on earlier work by Cotterill and Jackson (1984) attempted to clarify the practical basis of assigning economic weights "by getting rid of the word economic". From a forest tree breeding context, they defined several ways to determine economic coefficients, "which have little to do with market forces or economics". These methods included 'equal emphasis', 'desired gains' and 'partial regression'. It must be noted however, that these coefficients should not be thought of as economic weights in the true sense of Hazel's (1943) definition.

The concept of equal emphasis assumes that a proportional change in one trait is of equal importance to the breeding objective, as a change of the same proportion in another trait (Cotterill and Jackson 1985). It assumes, for example, that an improvement of 30% in harvestable volume is as important as a 30% improvement in basic density which in turn, is as important as a 30% improvement in pulp yield. A common variation on this concept was to consider changes of one phenotypic standard deviation in each trait to be of equal value (e.g. Shelbourne and Low 1980). Christophe and Birot (1983) suggest that the weights determined by this sort of approach should be termed 'weighting coefficients' rather than economic weights. Shelbourne (1997) reports some early unpublished New Zealand work carried out on radiata pine where economic weights were arbitrarily defined by the process of equal weighting. Wilcox and Smith (1973) presented an aggregate genotype objective using specific gravity, wood brightness and specific light absorption coefficient (a decent indirect measure of lignin content- Wilcox 1973) as selection criteria. In the analyses made however, all three traits were assigned equal economic values and hence the conclusions reached may be less than optimal.

The concept of desired gain is described in detail by Pesek and Baker (1969) and Cotterill and Jackson (1985). This approach requires that breeders specify the relative amount of improvement they would like (or desire) to achieve in each trait included in the selection index. It is then mathematically possible to work backwards to calculate a set of weighting coefficients which produce predicted gains in individual traits in the index that are proportional to the desired gains specified by breeders (Cotterill and Jackson 1985). This approach was used to calculate economic coefficients by Dean *et al.* 1983, Dean *et al.* 1986, and Dean *et al.* 1988 in Australia for radiata pine, *Pinus carribaea* and hoop pine respectively. To help determine desired gains Christophe and Birot (1983) suggested that breeders should define an 'ideal type' (ideotype) tree, with the difference between the mean of the present population and the ideotype for each trait being the desired gain. However one aspect of this approach is that intensive economic analyses and market forecasts are required (Cotterill and Dean 1990).

Cotterill and Jackson (1985) outline a partial regression approach to estimating economic weights. The method outlined involves the partial regression of traits measured at a juvenile age on estimates of the subsequent net economic worth of the same trees at the end of the rotation. The regression coefficient in this case may be loosely defined as the economic weight and estimates the dollar value by which net economic worth changes as the measured value of each juvenile trait is increased by one unit; other traits held constant. This method of partial regression has been used by Andrus and McGilliard (1975) in animal breeding. Bridgwater and Stonecypher (1979) employed a similar method of simple regression to estimate economic weights for *Pinus taeda.* One major flaw in this method, however, as discussed by Cotterill and Dean (1990) is that economic weights, estimated as regression coefficients, may be seriously biased by environmental covariances which happen to occur between traits. An appealing alternative to partial regression weights is to employ indices which use juvenile-mature correlations to try to maximise gains in mature traits as a consequence of selection on early traits (Cotterill and Dean 1990). Juvenile-mature correlations must be known in this case, along with the net economic worth of mature traits. This method has been used in selecting radiata pine in Australia (see Cotterill and Dean 1988, Dean and Cotterill 1991).

6.5 Defining the Breeding Objective

6.5.1 Profit Functions

The breeding objective is commonly described by a profit function, which relates genetic values (the function input) to a definition of profit (the function output). The current consensus approach to the derision of profit functions in the animal breeding literature (see Goddard 1998) is similar to the method advocated by Amer and Fox (1992). The following section presents this method with the objective assumed to be an economic one, loosely termed "profit". The exact definition of this objective is provided later in the chapter.

Hazel (1943) described an objective that was a linear combination of traits in which the coefficient of each trait was its effect on profit when all other traits were held constant. However, the relationship between a trait and profit may be non-linear (Goddard 1983, Weller 1994). Hence Goddard (1998) defines the profit function more generally as a "procedure or rule that takes genetic values of various traits as input and produces profit as output". For most purposes, a profit function can include an unknown constant because the profit function represents changes in profit caused by relevant changes in genotype.

The profit function may include variables controlled by management decisions (e.g. the rotation age), however this inclusion is only necessary if the management variables interact with genetic values to determine profit. For example, different given pedigrees of trees may have a defining limit of latewood to juvenile wood at rotation age. A given pedigree may reach this defining limit sooner and thus it would be more profitable to harvest these trees at an earlier age. When the profitability of genotypes is compared, each should be evaluated with the management variables set to their optimum value for that genotype. The profit function, expressed as either an explicit non-linear formula (Moav and Hill 1966) or a bio-economic computer model of the forest production system (Greaves 1999), can be written as:

$$PROFIT = \int(G; M) \qquad (6.34)$$

where:

- $PROFIT$ is the profit of the production enterprise defined;
- G is a vector of the mean genetic values of the breeding population (one vector per trait); and

- M is a vector of the management-controlled variables.

The profit function can be used to compare individual trees, pedigrees, or genotypes that differ at specific genes or transgenes. In other words, the profit function, as defined here, is not affected by how a genetic change is brought about but instead describes the effect of that change on profit. If differences in individuals or genotypes under consideration are small relative to the curvature of the profit function, then it is reasonable to approximate the profit function by a linear function (Goddard 1998). This linear approximation (which is likely to be acceptable when, say, selection is between genotypes of the same pedigree) is:

$$PROFIT = w'G \tag{6.35}$$

where:

- w is the vector of economic weights, following:

$$w = \frac{\partial f}{\partial G}(G_c; M_0) \tag{6.36}$$

where:

- $\frac{\partial f}{\partial G}$ is evaluated at the current mean genetic value (G_c) and the values of management variables that are optimal for the current production enterprise (M_0) – see Moav and Hill (1966) and Goddard (1983).

The economic weight for a given trait depends on what other traits are included in the profit function (Goddard 1983). In other words, the economic weight depends on which other traits are held constant when the partial derivatives are taken. An example of how this may affect the economic weight of a particular trait is given by Goddard (1998) for the case of animal growth rate. He shows that the economic weight of increasing growth rate when feed intake is held constant is not equivalent as when feed conversion efficiency is held constant.

The economic weights (w) calculated for a given production enterprise are equivalent whether the management control variables (M) are fixed at the current optimum or continuously re-optimised as the mean genetic values of the breeding population (G) change, provided that M_0 is an optimum with:

$$\frac{\partial f}{\partial M}(G_c, M_0) = 0 \tag{6.37}$$

This equivalence only applies to the linear approximation and hence only to small changes in G. For larger genetic changes, the reoptimisation of the management

variables for the new genotype has been shown to substantially affect the relative economic weights (Amer *et al.* 1994).

6.5.2 Definition of Profit

There has been a wealth of debate in the animal breeding literature on a number of connected issues dealing with the concept of how profit should be defined. The main issues are:

- from which perspective profit should be viewed (e.g. from the perspective of the forest grower, the industry or the consumer; see Moav 1973);
- how should profit be expressed, for example per unit area of forestry plantation or production enterprise, per tree, or per unit of product (e.g. cubic metre of wood or squared metre of finished paper); and
- what should the economic objective be maximising (i.e. should the objective be a profit margin: $PROFIT = I - C$, where I is the total income and C the total costs; or a ratio of I/C ? (Maximising I/C is equivalent to minimising C/I) (see Dickerson 1970, James 1982).

The decisions surrounding how to define profit, however, only affect the relative economic weights if the defined profit function makes the enterprise appear to be very highly profitable, or alternatively if the management variables have not been optimised (Goddard 1998). If profit is high, then we could assume that an increase in the scale of the enterprise would also mean an increase in income (I) and costs (C), and the product also proportionately increasing the profit margin ($PROFIT = I - C$). However, in this case the ratio of I/C remains unchanged- i.e. profit per producer is increased but not the unit of product and hence the producer but not necessarily the consumer benefits.

It is more likely, however, for very high mean values for profit to be due to an inadequacy in the profit function than a description of reality. Goddard (1998) surmises that if an enterprise is indeed highly profitable, then others will invest in it until its profitability is similar to that of other sectors of the economy. Brascamp *et al.* (1985) argue that when the normal return on investment is included as a cost, the mean profit is zero. However, individual enterprises may be more profitable than average and, hence not at zero profit (Goddard 1998).

A number of methods have been proposed to accommodate the distortion of economic weights caused by profit functions with a non-zero mean:

- change the economic model so that when normal return on investment is included as a cost, the current profit is equal to zero (Brascamp *et al.* 1985);
- subtract from profit the change that is due to a change in scale (Smith *et al.* 1986);
- define the objective as a ratio of I/C (Dickerson 1970); and
- increase the scale of the production system until an optimum is reached (Amer and Fox 1992).

The effects of these four proposals to overcome distortions in economic weight estimation and the conditions under which economic weights derived in different ways are equal are discussed in the following section "Rescaling the Profit Function". Although the purpose of this paper is to present the current thoughts on how to define a breeding objective for forestry based production enterprises, the Brascamp *et al.* (1985) concept of zero profit and the extension of this theory by Smith *et al.* (1986) will be briefly discussed.

6.5.2.2 Concept of Zero Profit

As mentioned previously, Brascamp *et al.* (1985) established that when the profit required by an enterprise to stay in business in the long term (normal profit) is included as a cost in the profit function, economic bases will be the same for all bases considered. In other words, if profit is set to zero by transferring it as a cost of production then the relative economic weights are equivalent for all interests and for any unit of evaluation. Considering a hypothetical production enterprise in which the income to producers was appropriate to the given economic and social environment, the concept of zero profit (including that of setting the profit to zero by considering it as a legitimate cost) was rationalised by Brascamp *et al.* (1985). If the income received was increased, the enterprise accountants may suggest an increased investment to obtain more profit. Increase in profit by increased production output may hold in the short term for an individual producer, but not for all producers (Brascamp *et al.* 1995). This is a simple matter of supply and demand (Weller 1994), whereby increased supply will lead to a decrease in the price per unit. Increases in profit by reduced costs will also encourage extra production leading again to reduced prices. The general result is that improvement of components of the profit equation will not, in the long term, affect profit for the group of producers, but will lead to lower consumer prices. Hence, profit in a stable situation will correspond to the 'normal profit' of economic theory (Stainer and Hague 1980). 'Normal profit' is the profit required for the producer to stay in business in the long term (applying in conditions of perfect competition between producers). Economic theory defines normal profit as an average cost, and hence

the average long term real profit in an industry at equilibrium is zero (Stainer and Hague 1980). This corresponds to setting profit to zero in deriving relative economic weights (Brascamp *et al.* 1985).

6.5.2.3 Subtracting Change From Profit

The work of Brascamp *et al.* (1985) was extended by Smith *et al.* (1986) who showed that the expression of fixed costs per unit of output and rescaling the size of the production system to match genetic change in output, input or profit also resulted in equivalent weights for different bases.

Costs may be split into fixed costs and variable costs. Fixed costs are generally those incurred in running the production enterprise and include costs such as labour, finance, buildings, machinery and the producer's margin. Variable costs are usually associated with the individual and include costs (in the case of a forestry enterprise) of planting, maintenance, harvest, transport and energy consumption in processing. The method of dealing with fixed costs is important in estimating economic weights. Smith *et al.* (1986) argue that fixed costs are dependent on the level of output and should be included with other costs per unit of output. This argument is justified by the long term nature of genetic improvement. Prior to investment, all costs are variable costs, since no fixed investment has been made. In addition, at each new investment, the amount invested in fixed enterprise costs depends on the level of output planned. The same applies when considering output over a long term or the industry-wide output with many producers and continuous investment.

Another factor worth considering when deriving economic weights is that resources should be assumed to be optimally, efficiently used in production. This implies that changes which correct or benefit from previous inefficiency should not be counted. This can be envisaged in a forestry context if a greater volume of wood is produced from a given plantation stocking level (i.e. increasing individual tree growth): if the extra volume of wood can be fitted into the original production enterprise with no increases in fixed costs then the original enterprise must not have been at maximum efficiency. If the enterprise was already at maximum efficiency then a proportional increase in the production facility and its fixed costs would be required. This means that fixed costs, as with variable costs, should be expressed per unit of output, rather than as a fixed total enterprise cost (agreeing with Dickerson 1970 and Smith *et al.* 1986). Hence, selection for traits to redress inefficiencies in a production system is of specific and temporary value rather than of general value, and is at the opportunity cost of selection for traits which save costs per unit of output (Smith *et al.* 1986).

Smith *et al.* (1986) suggest that any extra profit from genetic change that could also be obtained by altering the size or rescaling the operation should not be counted in assessing the value of genetic improvement. This is because a producer can change profit, without genetic improvement simply by rescaling the production enterprise. Thus the economic value of genetic improvement comes from reducing costs per unit of product value, rather than changing the output (Simmonds 1974, Smith *et al.* 1986).

Traditionally, the theory of profit equations does not allow for the fact that changes in output and profit can also be obtained by rescaling the production enterprise, without any genetic improvement. Hence any extra profit due to changes in output, which also could be obtained by rescaling, should be subtracted from the differentials to get the "true" economic weights (Smith *et al.* 1986). With optimal or efficient use of resources there will be no slack in the production system, and so increased production will require extra resources. The real profit comes from reducing the cost of production per unit of product value or increasing the unit volume of products produced.

MCArthur (1987) however, criticised the work of Smith *et al.* (1986) arguing that a producer faces decreasing marginal returns with an increase in the scale of the enterprise and hence if operating at maximum efficiency, the producer could not scale up its output without a loss in profits.

6.5.2.4 Neoclassical Production Theory

Neither the methods of Brascamp *et al.* (1985) or Smith *et al.* (1986) uses formal production economics theory (as advocated by Amer and Fox 1992) when addressing the problem of differences in economic weights. As a result, the determination of the level of output for the producer, before and after, genetic improvement appears arbitrary when viewed from the perspective of neoclassical production theory (described by Debertin 1986).

This theory has evolved as economists have attempted to explain the behaviour of competitive firms in transforming basic materials (i.e. wood) into goods (i.e. timber and paper) desired by consumers. The goals of forest managers are assumed to be profit maximisation or cost minimisation, which can be relaxed to accommodate uncertainty (Robinson and Barry 1988). The model described by Amer and Fox (1992) is set from a long term perspective which is in agreement with conventional theory dealing with technological change (Lipsey *et al.* 1985). In the long term, costs such as capital investment, which are considered to be fixed in the short term, are treated as variable costs (Epp and Malone 1981). Indeed, genetic improvement programs involve considerable development and adoption time periods (Amer and Fox 1992). This, in conjunction with differences in the short

term constraints of individual firms making up the forestry and forest products industry (Smith *et al* 1986; see previously) suggest that a short term planning horizon is inappropriate (Amer and Fox 1992). This is of even more relevance to the genetic improvement of forest trees (Klemperer 1996).

6.5.3 Rescaling the Profit Function

As a component of the profit function, there is usually one management controlled variable that indicates the scale of the enterprise. For example, that variable might be the number of trees in a plantation (n), so that:

$$\int(G;n) = n(I - C) - FC \qquad (6.38)$$

where:

- G is the vector of mean genetic values of the plantation (one per trait);
- I is the income derived from each tree;
- C are the costs per tree; and
- F are the fixed costs.

Smith *et al.* (1986) however, have argued that in the long term, all costs are variable and assume that all costs are proportional to the scale of the enterprise so that $F = 0$. Under this method, there is no optimum value for a scale variable and therefore the normal procedure of comparing genotypes under optimum management may not be followed (Goddard 1998). If $F = 0$, then the choice of a value for n is arbitrary as the economic weights are simply proportional to n.

The scale of a forestry/forest-products enterprise can be described by variables other than the number of trees, leading to other descriptions of the profit function. The scale of a forestry enterprise for instance may also be described by the plantation area (Ha), following:

$$\int(G;Ha;n) = Ha[s(I - C)] - FC_{Ha} \qquad (6.39)$$

where:

- s is the stocking density, a management controlled variable that is optimised; and
- FC_{Ha} is the fixed cost per hectare.

In this description, the fixed costs are assumed to be proportional to the scale variable *Ha*.

The use of different scale variables can lead to different economic weights (see following proofs). Amer and Fox (1992) regarded the scale of an enterprise as a management variable, proving the equivalence of different descriptions of a profit function. Goddard (1998) also provides formulated proof of the equivalence of different profit equations. The following proof is adapted from those formulated by Gibson (1989), Amer and Fox (1992) and Goddard (1998):

Consider transforming from $f_1(G;n)$ to a profit function $f_2(G;m)$ based on some other scale variable m, such that $m = n \times x$ (where x is a product, cost, or trait per individual), then:

$$PROFIT = f_2(G;m) = f_1(G;\ n(m,G))$$

and differentiating we obtain:

$$\frac{\partial f_2}{\partial G} = \frac{\partial f_1}{\partial G} + \frac{\partial f_1}{\partial n}.\frac{\partial n(m,G)}{\partial G} = \frac{\partial f_1}{\partial G} - \frac{\partial f_1}{\partial n}.\frac{n}{x}.\frac{\partial x}{\partial G}$$

where:

$\frac{\partial f}{\partial G}$ is the economic weight for a given variable.

This formula can be used in several situations:

1) If n is optimised such that $\frac{\partial f_1}{\partial n} = 0$ then:

$$\frac{\partial f_2}{\partial G} = \frac{\partial f_1}{\partial G}$$

This result proves the principle of equivalence of different profit equation descriptions, as used by Amer and Fox (1992). When scale is treated as a management variable and optimised there is no profit obtained by increasing scale. This method would seem intuitively logical, however the complexity in modelling the effect of changes in scale and defining an optimum may detract from it.

2) If f1 is linear in n so that $\frac{\partial f_1}{\partial n} = I - C$ and no optimum exists, then:

$$\frac{\partial f_2}{\partial G} = \frac{\partial f_1}{\partial G} - \frac{I-C}{x}.\frac{\partial x}{\partial G}$$

For instance:

a) if $(I-C) = 0$, because there are no fixed costs and mean profit =0, then:

$$\frac{\partial f_2}{\partial G} = \frac{\partial f_1}{\partial G}$$

In other words, with no fixed costs and zero profit, the choice of scale does not affect the economic weights (Brascamp et al. 1995).

b) if the total income (I) is restricted by x (ie. $x = I$), then:

$$\frac{\partial f_2}{\partial G} = \frac{\partial f_1}{\partial G} - n\left(1 - \frac{C}{I}\right)\frac{\partial I}{\partial G} = \left(\frac{C}{I}\frac{\partial I}{\partial G} - \frac{\partial C}{\partial G}\right)n$$

This rescaling is recommended by Smith et al. (1986).

Again if *PROFIT* = (I – C) = 0, then:

$$\frac{\partial f_2}{\partial G} = \frac{\partial I}{\partial G} - \frac{\partial C}{\partial G} = \frac{\partial f_1}{\partial G}$$

c) if the producer must not exceed a quota on trait 1, then:

$x = g_1$, $m = ng_1$ and $\frac{\partial f_2}{\partial G}$ are the economic weights under quota given by:

$$\frac{\partial f_2}{\partial G_1} = \frac{\partial f_{12}}{\partial G_1} - \frac{I - C}{G_1}$$

for the trait under quota, and

$$\frac{\partial f_2}{\partial G} = \frac{\partial f_1}{\partial G}$$

for other traits (Gibson 1989).

The scale variable in essence imposes a constraint on the enterprise because the economic weights are calculated with the scale variable held constant. The choice of constraint becomes important when profit is not zero or when fixed costs are not proportional to the scale variable, as shown above. The existence of fixed costs depends on the time frame considered. For example, in the future, forest growers may be constrained by a quota (see proof 2c above). For a forest grower operating within this quota, genetic change resulting in increased production would require a reduction in the number of trees. Although in the short term, there are likely to be fixed costs that can't be reduced, in the long term these resources will be diverted to other enterprises, and there may be no fixed costs (i.e. all costs will be proportional to the number of individuals, the level of production or other traits included in the profit function – Goddard 1998).

Goddard (1998) suggests that the larger changes in economic weights that have been observed when the constraint or scale variable is changed may be due to an inappropriate treatment of fixed costs. For example, if the scale variable is the number of trees planted each year (see Van Arendonk and Brascamp 1990 for an example from an animal breeding perspective) then increasing the rotation age

implies increasing the size of the forest estate at any given time, hence increasing fixed costs that must be included in the profit equation.

The need to consider rescaling as recommended by Smith *et al.* (1986) most likely arises due to some cost components being excluded (Goddard 1998). Their method of rescaling is, in effect, equivalent to assuming that the missing costs are proportional to existing income or costs and, hence, they increase as total returns or costs increase.

When implementing the method of setting profit to zero, as described by Brascamp *et al.* (1985), the method of implementation appears crucial. If fixed costs are added until profit is zero, there will be no change in economic weights for the enterprise. Goddard (1998) argues that it seems more likely, at least in the long term, that these extra costs will be proportional to numbers of individuals, plantation area, production level, or other existing costs. How these extra costs are apportioned will affect the economic weights. In this case, costs should not be arbitrarily added to achieve zero profit, but a profit considerably greater than zero should be taken as a warning that some costs may have been excluded.

Amer and Fox (1992) argue that all management variables, including the scale variable, should be optimised before economic weights are calculated. An optimum value for the scale of the enterprise might exist because of the fertility of a particular forest site or due to the constraint placed on the pulping process (e.g. recovery boiler). In this case, the trade-off causing such an optimum need to be included in the profit function, and economic weights might be affected.

Goddard (1998) concludes that an attempt should be made to account for all costs and to assign them correctly to the variables that determine them in the long term. This procedure allows a check to be made that profit is close to zero. If some costs are hard to apportion, the scale variable should be chosen so that these costs can be assumed to remain constant while the scale variable is held constant (e.g. choosing land area as a scale variable).

6.5.4 Units of Profit

Profit functions have thus far been used that predict profit per forest or firm, and such use is deemed logical by Goddard (1998) because it is the firm that must make decisions about its breeding program and that will attempt to maximise profit (Amer and Fox 1992). A national industry may be considered simply as a large firm.

Profit can also be expressed, for example, per tree, per dollar total cost, or per tonne of paper sold. For instance:

$$\frac{PROFIT}{n} = \frac{\int(G;n)}{n} \qquad (6.40)$$

represents profit expressed per tree (n) for a plantation with a fixed maximum stocking rate. For any given unit x, the economic weights (following Goddard 1998) are:

$$\frac{\partial}{\partial G}\left(\frac{PROFIT}{x}\right) = \frac{1}{x^2}\left(x\frac{\partial PROFIT}{\partial G} - PROFIT\frac{\partial x}{\partial G}\right) \qquad (6.41)$$

If x is the scale or some given management variable with $\frac{\partial x}{\partial G} = 0$ then the relative economic weights of $\frac{PROFIT}{x}$ are equivalent to those *PROFIT*. If mean profit equals zero, then relative economic weights are equal regardless of the choice of x (Smith *et al.* 1996). The relative economic weights are the same for $\frac{PROFIT}{I}$, $\frac{PROFIT}{C}$, $\frac{I}{C}$, and $\frac{C}{I}$, where:

$$PROFIT = \int(G;n) = n(I - C) - F \qquad (6.42)$$

and these weights are equivalent as for the rescaled (following Goddard 1998):

$$PROFIT = f_2(G;I) \text{ or} \qquad (6.43)$$

$$PROFIT = f_3(G;C) \text{ if } F = 0 \qquad (6.44).$$

6.5.5 Perspective to Consider Economic Weights

Moav (1973) suggested three bases for which profit can be expressed, corresponding to the interests of the industry as a whole, an existing small farmer (or forest grower), and the consumer. Using these three bases, Moav (1973) expressed profit as a linear function of a series of variables which included several different traits as well as fixed and variable costs. Economic weights for each trait were then calculated as the partial derivative of profit with respect to a unit change in the trait concerned, following Equations (6.41) and (6.42) detailed above. Variations in the linear profit functions when expressed according to the three different bases resulted in different partial derivatives with respect to a unit change

in the trait. Hence Moav (1973) showed that the profit equation, and the economic weights derived from it, depends on the perspective taken. Ideally the improved genetic stocks have to serve all interests simultaneously since all are involved in the same production system (James 1983). Logically, the perspective depends on who is being asked to invest in the breeding program, but fortunately the type of investor should make little difference (Goddard 1998).

Suppose that profit is evaluated for a vertically integrated enterprise (i.e.. one that breeds its own seedstock and sells a product to consumers). The profit function derived would be equally applicable to an enterprise that sells seedstock provided that market signals are transmitted up the marketing chain. In other words each participant in the chain gets paid according to the value of their product to the purchaser. This profit function would also be appropriate from the consumer's point of view. In reality however, it is more often the case that market signals are not always relayed from consumers to breeders, which distorts the objectives of seedstock producers. For the industry as a whole, the profit function for the integrated enterprise is the correct way for assessing economic weights even if market signals are not directed up the marketing chain. This is because the benefits of genetic improvement are captured by some participants, and competition will eventually cause them to be passed on to other parts of the industry.

The breeding objectives of individual producers, who may be receiving distorted market signals, are expected to differ from those of an integrated firm. Genetic change takes time to occur and because of this, the individual producer must predict the prices that will apply in the future. Assuming that market prices become more rational over time, these prices are likely to be a blend between current (distorted) prices and the prices that would be paid in a value-based marketing chain.

De Vries (1989) considers the effect of competition between seedstock sellers such as breeding companies. He assumes the seedstock buyers tend to set minimum levels for each trait. Consequently, the economic weight from the perspective of the seedstock seller increases as the mean of the stock fall below the mean of the competitors. If the objective used by seedstock buyers is the correct objective for their enterprise, then the competition between sellers has no effect on the seller's objectives. If buyers of seedstock are buying using an objective that differs from the profit function appropriate to their own seed orchard, then this is another example of distorted market signals causing distorted breeding objectives.

For a small enterprise supplying only a small portion of a larger market, it may be assumed that genetic improvement has a negligible effect on market price. However, this may not be the case when considering the industry-wide perspective.

For example, the genetic improvement of plantation forest trees may lead to an increased supply of timber and consequently a depression in price. The 'Marshall' approach to economic surplus, as used by Amer and Fox (1992), shows that constant price profit function approximately predicts the benefits to the community as a whole. This approach is based on the way in which supply of a product and demand for it change with its price. The genetic improvement of forest trees makes timber cheaper to produce (a benefit to producers), so more timber being produced may lead to a price fall (a benefit to consumers). The division of these benefits between producers and consumers depends on the elasticities of supply and demand. If genetic change does not alter the elasticities of supply and demand, the relative economic weights are unaffected by accounting for the change in price caused by genetic improvement.

In summary, a profit function for a vertically integrated enterprise with optimised management and that can not gain by increasing the scale of the enterprise is widely applicable.

6.5.6 Traits to Include in the Profit Function

A critical prerequisite when defining any breeding objective is to distinguish between traits in the objective and traits in the selection criterion. Clarke and Ray (1977) and Ponzoni (1979) were amongst the first workers to distinguish between the factors that are measured (the selection criteria) and the traits directly affecting profitability and which therefore comprise the breeding objective. The conventional approach to selection of breeding stock is to define an objective and then use knowledge of genetic and phenotypic covariances to define a selection criterion. Hence the choice of selection criteria will be influenced by which traits are part of the breeding objective (Woolaston and Jarvis 1995), but the reverse should be avoided as it may lead to the omission of economically important traits (James 1987). In the strict application of this approach, covariances have no place in the definition of the objective (Goddard 1998). Therefore, the traits in the profit function (breeding objective traits) should relate as directly as possible to the sources of income and cost, and the profit function should be as close as possible to true profit. An obvious example in forestry, provided by Woolaston And Jarvis (1995), of where a selection criterion is not a breeding objective goal is the use of pilodyn measurements to provide information on wood density. A tree's pilodyn measurement has no value *per se* but it does provide valuable clues to the genes that the tree is carrying for wood density, which more directly influences profitability. Decisions regarding which traits to include in the profit function should ideally be based on economic grounds alone (Woolaston and Jarvis 1995). Traits should not be excluded on the basis of a lack of information (James 1982) or

on the fact that they may be difficult to measure (Woolaston and Jarvis 1995). Realistically however, Goddard (1998) concedes that there is little point in the inclusion of a trait with no genetic variation. Harris (1970) lists three points to consider when deciding which traits to include in the profit function:

- economic importance;
- potential for genetic improvement (from direct selection relative to correlated response to other traits; and
- cost of measurement in labour, facilities, and time (generation interval).

In other words, Harris (1970) suggests that the decision of which traits to include in the objective depends on the additional amount of economic improvement that can be made relative to the 'cost' of making that improvement. Greaves *et al.* (1997) listed kraft pulp yield among other traits in their cost function, which establishes a breeding objective for kraft pulp production from *Eucalyptus nitens*. Only a limited amount of genetic variation has been shown for this trait and the expense of measuring it is high (around Aud $500 per sample; Phil Whiteman, *pers. comm.*). Tree breeders may opt to measure, for example, only a few individuals per family and base breeding value estimates for each individual within that family on the mean of these few measurements. However, this greatly reduces the reliability of the information we are using on an individual tree basis (Mrode 1996). The recent advance in using NIR spectroscopy to evaluate the kraft pulp yield potential of an individual tree lowers the measuring cost greatly and looks like a promising alternative to the traditional pulp yield digestions (Carolyn Raymond, *pers. comm.*)

Cotterill and Dean (1990) recommend that tree breeders should try to minimise the number of traits in the breeding objective, but Woolaston and Jarvis (1995) argue that this is unnecessary if sound economic and genetic information is available for all traits affecting income and expense. Indeed, Gjedrem (1972) concluded that all traits of economic importance should be included in the definition of a breeding objective. It is important to realise that the omission of a trait is equivalent to defining the economic value of that trait to be zero. Goddard (1998) state that profit functions that leave out some traits can lead to sub-optimal decisions. Goddard (1998) discusses an example for dairy cattle breeding, and explains that by ignoring fertility, health costs and feed costs, the economic benefits to be expected from selection for increased milk yield may be exaggerated, while the benefits from including these traits among the selection criteria may be overlooked. Similarly, a trait should not be replaced by a prediction unless that prediction is 100% accurate. If a trait is left out, it should be predicted from the other traits

using genetic regression because we are predicting one breeding value from other breeding values (Goddard 1998).

In practice, income and costs tend to be properties of the forest plantation rather than of individual trees, so some degree of modeling is necessary. For instance a trait such as mean annual increment (MAI) changes with the age structure of the forest, which, in turn depends upon survival rates. It is possible to model the economic effect of changes in survival rates by calculating the effect on plantation age structure and hence, MAI (see Chambers and Borralho 1997- "Chapter XX"). However, assumptions about covariances should, if possible, not be incorporated into the profit function but should be stated explicitly in matrices of genetic parameters (Goddard 1998). An exception to this advice given by Goddard (1998) might occur if the traits that are directly related to income and costs were subject to large interactions of genotype and environment (G×E) or nonadditive genetic effects. If these traits could be replaced by traits that did not show G×E this substitution could be an advantage (Goddard 1998). However, in this case the advantage of simpler genetic models is balanced by a more complicated model connecting the traits to profit.

The exact definition of the traits that determine profit may also require further attention. For instance, it is the growth rate of a forest plantation that is important, which is not the same as the growth rate of an individual tree within that plantation. For example, Goddard (1998) based on work by Muir (1996), presents an animal breeding example: an aggressive pig may have a higher growth rate but may depress the growth rate of all other pigs in the pen. Competition effects in forestry situations immediately spring to mind. In this case the objective would need to be modified to include the new 'mean' trait. An alternative analysis would be to recognise that the growth rate of one individual is affected by its neighbours in the plantation (from Griffing 1967) and include a trait to this effect in the profit function.

6.5.7 Estimation of the Profit Function

Van Arendonk (1991) demonstrated the use of profit equations to determine relative economic weights, and distinguished two methods to estimate economic weights (or, in a more general sense, the parameters of a profit function). The bio-economic model approach accounts for sources of income and costs directly. The second, regression approach uses field data to estimate a multiple regression equation that predicts profit (Melton *et al.* 1994). However, as Goddard (1998) discusses the second method may be confusing breeding objectives and selection criteria, and at the very least the regression should contain genetic and not phenotypic

covariances. It seems to be the current consensus to base the profit function on a bioeconomic model with the estimation of covariances used in choosing selection criteria.

6.5.8 Long-term Considerations

Until this point, a profit function has been described which answers the question: "If the current plantation could be replaced by a new plantation with different genetic values, how much would profit change?". Particular to forestry however is the long term nature of the business. Genetically improved trees will not reach maturity for at least 15 years for a pulp-wood rotation and often much longer for saw-log rotation (Shelbourne *et al.* 1997). Furthermore, the different costs and income in forest tree breeding procedures are realised at different times, and with different probabilities. Thus factors that affect costs and income over the long-term must be considered in the economic evaluation of genetic differences. Long term considerations will affect both the attractiveness of investment in breeding programs and the relative economic values of the individual traits included in the profit equation (Weller 1994). The primary long-term considerations of importance to tree breeding are the discount rate, risk, profit horizon, and juvenile flowering (reproduction rates).

The time taken for genetic change is important in two ways:

- the time taken reduces the value of the genetic change, which affects decisions regarding how much to invest in a breeding program; and
- if the changes occur at a faster rate in some traits than others, it could affect the relative economic weights.

These issues can be alleviated by discounting the value of genetic change in future years (all future income) resulting from a specific decision to a net present value (e.g. McClintock and Cunningham 1974). This is based on the premise that an economic benefit of a specific magnitude is more desirable today compared with its value deferred to some time in the future. A discount rate (d) is employed, which is conceptually the inverse of a compound interest rate (Miller and Pearson 1979):

$$d = \left(\frac{1}{1-i}\right)^t \qquad (6.44)$$

where:

- t is the time in years from some fixed date, for example the date of plantation establishment (as used by Borralho *et al.* 1993, Greaves *et al* 1997), or date of first income received; and

- i is the appropriate interest rate.

This value is simply multiplied by any cost or income incurred or gained.

Poutous and Vissae (1962) and Soller *et al.* (1966) were amongst the first to use this discounting concept. Cunningham and Ryan (1975) explored the effect of varying discount rates and time horizons on the net benefit from breeding programs, using cattle as an example. This sparked debate with respect to which discount rate is appropriate to use in a breeding concept. Conventional advice is that the discount rate should be the real or inflation-free interest rate (Smith 1978, Goddard 1998). Although nominal interest rates and inflation rates have varied dramatically in many societies, Smith (1978) showed that long term interest rates have remained remarkably constant in the range of 3 to 5 percent. The 'real' interest rate value recommended by Smith (1978) is 3%. However the relevant interest rate is most likely to be the rate paid on forest land and growth debt because for most forest managers, retiring forest debt is an alternative investment. Goddard (1998) adds two adjustments to this proposal:

- the decline in terms of trade for the products sold (i.e., the amount by which the price of forest products fall behind inflation). If it is intended to include benefits to consumers, then the decline in forest product prices caused by genetic improvement should not be included in the discount rate because it represents a benefit to consumers.

- the decline or increase in volume of product sold by the users of the genetically improved stock.

As with any long term investment, there is also a need to add a loading to account for the risk that the increased profit will not be received. It may be the case, for example, that the assumed genetic gain to be made will not be achieved, or alternatively that the future market will value a given product less favourably than expected. This second scenario implies that the assumed profit function has changed.

Although discounting is extremely important when assessing the total value of a genetic change, there is very little evidence that discounting has altered the relative economic weights to any great extent in the animal breeding literature. However, with the longer rotation lengths in forestry, and the increasing importance of a compounding discount rate with time this may need more investigation from a

forestry perspective. An exception to this could occur however, if different discount rates were applied to different traits (Goddard 1998). An example is Goddard (1992), who used different discount rates for additive genetic gain and for losses caused by inbreeding depression respectively. From a forestry perspective, this approach may warrant further attention, especially with the open-pollinated progeny currently dominating the local hardwood plantations in Australia.

Chapter 7

An economic breeding objective for plantation radiata pine grown to produce timber flitch and newsprint: (a) Development and sensitivity of the production enterprise model

Chapters 7 and 8 have been combined for submission as:
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7.1 Introduction

The first step in the design of any breeding program is to decide on its objectives (Goddard 1998, Chapter 6). However, as shown in the previous chapter, some issues in the definition of breeding objectives are still unresolved. Much of the debate over breeding objectives has centered around the perspective from which to view profit (i.e. producer or consumer). Moav (1973) suggested three perspective views for evaluating gain from animal breeding:

a) the society as a whole;

b) an existing producer; and

c) a new investor to the industry.

The respective objectives for (a) to (c) are to minimise cost, maximise productivity per unit of production and to maximise profit per unit of investment respectively. However, Brascamp *et al.* (1985) demonstrated that when production system profit is set to zero the various perspective views become equivalent, arguing that in the long term only operating profit can be assumed, which itself should be treated as a cost. Smith *et al.* (1986) demonstrated that economic value calculated as incremental profit could be an over-estimate of the true economic advantage of genetic improvement if a component of incremental profit could be attributed to an increase in the scale of the operation (Goddard 1998). In addition, Amer *et al.* (1994) argued that to define gain in terms of an existing enterprise structure may be too simplistic as the structure of an enterprise may itself need to evolve due to genetic improvement.

Particular to forestry is the long-term nature of the business. Trees planted today for the manufacture of timber or paper products may not reach final harvest for up to 25 years. During this time new mills may have been built and existing mills rebuilt or decommissioned. Similarly, markets for particular wood products may come and go. However, for a vertically integrated forestry and forest products company, the definition of improvement must be addressed in respect of the expected wood utilisation system 25 years into the future. As an initial approximation, the influence of various factors on the production system can be defined in respect of the wood utilisation systems in place today and risk analysis used to explore the impact of uncertainties on the conclusions drawn (Greaves, *in review*). A logical initial place to impose a boundary on any forestry production system is the growing forest. The costs in this case will be those of growing the forest, with returns (or income) derived from royalty on roundwood sold from the forest. Such a methodology however, assumes that variation in log royalty reflects variation in the true value of logs to the processor. If variation in a given wood characteristic, tracheid length for example, is not truly reflected in variation in log royalty to the processor, then a forest grower who is also a processor may not be maximising the financial potential of tree improvement. Further, as processors better understand the value of a change in the given wood characteristic, royalty structures will probably evolve to better reflect true log value. Hence even a forest grower who sells logs will be best served by correctly weighting traits as they influence true value to the processor.

Seventy percent of wood grown in unpruned radiata pine forests may be used to make pulp for paper products (e.g. Greaves 1999). Whilst current pulpwood royalty structures do not reflect variation in pulpwood quality, there is mounting evidence

that wood microstructure and chemistry may have considerable impact on the economics of pulp and paper production (see Chapters 4 and 5, Greaves *et al.* 1997, Shelbourne and Kibblewhite 1997, Shelbourne *et al.* 1997). Although it may seem far removed from the forest grower, this suggests that the production system boundary should include paper production. Large forestry companies today often include sawmills and paper-mills and for such organisations tree improvement must be defined in terms of overall profitability. In this case, the boundary of the production system must include both saw-milling and papermaking.

Ponzoni and Newman (1989) following Ponzoni (1986) define the methodology to derive a breeding objective function as:

a) specification of the breeding, production and marketing systems;

b) identification and definition of the wood-flows and the sources of income and cost;

c) determination of biological traits influencing wood-flow, income and cost; and

d) derivation of the economic value (economic weight) of each trait and the formal definition of a breeding objective.

This chapter represents the first piece of work in the development of a breeding objective for plantation grown radiata pine used to produce timber flitches and newsprint from thermomechanical pulp. It seeks to satisfy parts (a) and (b) of Ponzoni and Newman's (1989) four-stage methodology for the development of breeding objective. The boundary of the production system defined in this chapter includes both timber flitch and newsprint production components, which implies that changes in true timber flitch and newsprint value are reflected in the price of these products. Although it is assumed that the flitches are sold to a nearby sawmill for further processing, changes in the true value of processed timber to the sawmiller are also reflected in the price this sawmiller is prepared to pay for the flitches. As costs and income occur at different times in the production system, present value analysis was employed to accommodate differences in the timing of costs and income.

In discussing the application of economic indicators to long-term investment decision analysis, Anthony and Reece (1989) conclude that when choosing between investment options, the *Profitability Index* (ratio of total profit to total costs) is a better indicator than *Net Present Value.* The *Net Present Value* of different investment options can not be justifiably compared unless the investments are the same size. *Profitability Index* reflects the third perspective of economic advantage

as proposed by Moav (1973) and was used by Greaves (*in review*) in his definition of an objective aimed toward sawn structural grade timber and liner-board from radiata pine. *Profitability Index* was also used in the current study in preference to *Net Present Value*, or other economic indicators such as *Internal Rate of Return*.

Due to the sensitive nature of much of the information used in the development of an economic breeding objective, the approach taken throughout was to use the best available information, and then to identify critical assumptions using sensitivity analysis.

7.2 Methods

7.2.1 Defining the enterprise production system

The production enterprise was defined here as a closed system, where all merchantable wood that was grown was processed within the enterprise and sold as timber flitches and high brightness newsprint grade paper. Hence the boundary of the production system as defined, includes both flitch milling and papermaking (newsprint production). All sections of the enterprise were treated as if they were components of a single business, hence no transfer prices are paid for the movement of wood within the production system. Costs were incurred in growing, harvesting, transport, chipping/sawing, pulping and paper (newsprint) production, whilst income to the enterprise was received from the sale of timber flitches (to a near-by sawmill) and newsprint.

As all costs become variable in the long term (Epp and Malone 1981) all costs were treated as variable in this analysis. Processing costs such as newsprint production and pulping costs were treated as total unit costs (i.e. to include both fixed and variable components) unless otherwise specified.

The production system included activities spread over the 25-year rotation length of a plantation:

- plantation establishment costs were incurred at year "zero";
- plantation maintenance costs and land use costs were incurred annually over the life of the plantation;
- commercial thinning operations occurred at years 15 and 20 (termed "*T1*" harvest) and 20 (termed "*T2*" harvest) respectively, resulting in costs of

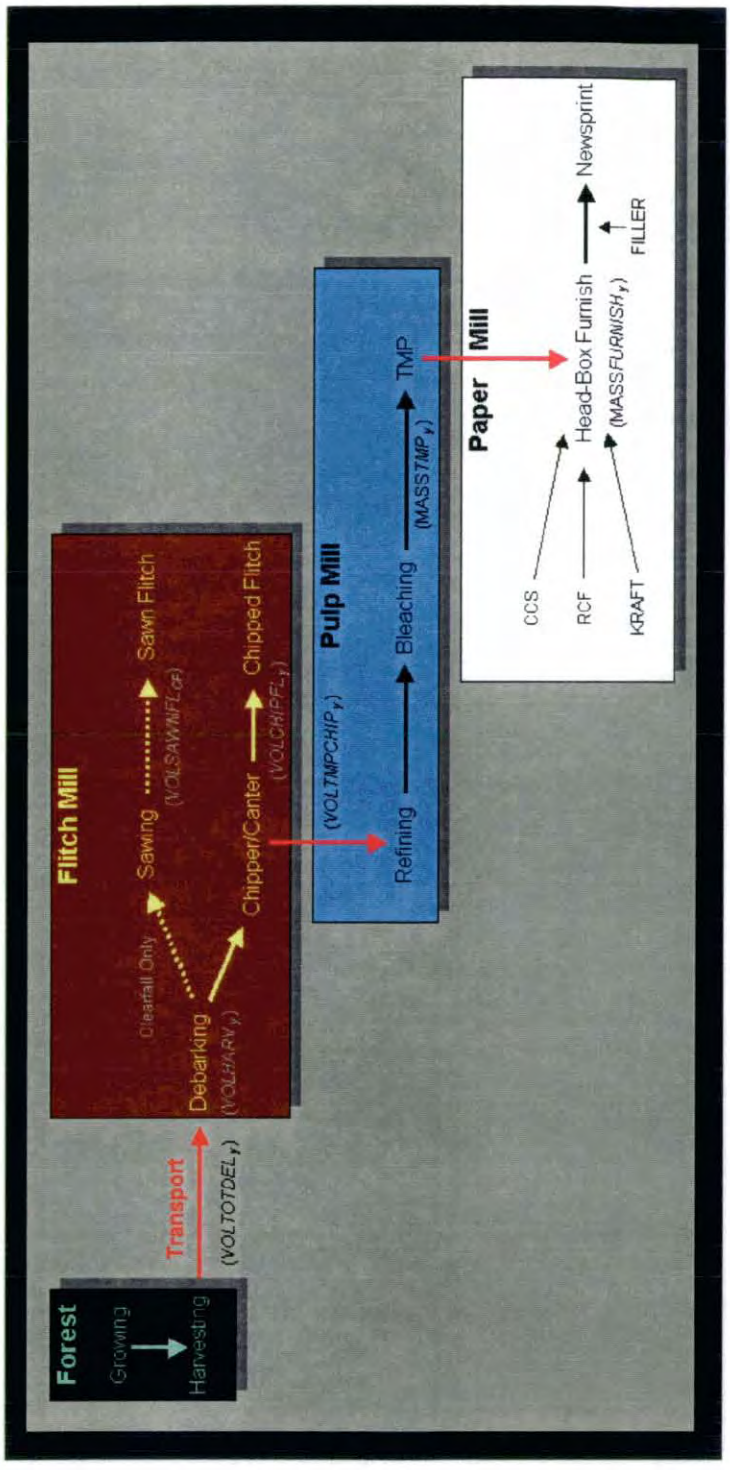
harvesting, transport, chipping/cantering, pulping and newsprint production, and returns from the sale of timber and newsprint; and

- the bulk of total costs occur at the end of the rotation (year 25) as do the bulk of the returns from selling timber flitches and newsprint.

A brief overview of the hypothetical production system is given in Figure 7.1 for harvesting operations T1, T2 and CF respectively. The hypothetical enterprise upon which this model is based is assumed to have such infrastructure in place, whereby the flitch mill and pulp and newsprint mills are situated at the same location. Hence there are no transportation costs for moving material between each mill. Harvested green logs are transported to the flitch mill where they are debarked before being chipped on a chipper canter. A proportion of the green logs are converted into timber flitches for sale to sawmills for further processing (Figure 7.1). However, the majority of the volume of wood entering the flitch mill provides wood chips for pulping (often termed "pulpwood"). In the case of clearfall harvesting, a proportion of the logs are considered to be of sufficient size and quality for direct sawing into flitches as opposed to the chipper-canter method used solely at T1 and T2 (Figure 7.1). Wood chips are cleaned and screened at several stages before being moved by means of a conveyer to the adjacently situated pulp mill.

Wood chips entering the pulp mill are steamed under pressure just prior to, and during, mechanical refining. Refining is simply the step-wise mechanical unraveling of the steam-softened wood chips into individual TMP fibres. Once screened and cleaned, the fibres enter the bleaching towers. It is assumed that the current enterprise makes use of a hydrogen peroxide bleaching process. Additional screening and cleaning stages follow bleaching, before the bleached fibres are blended with a number of other pulps. Similar to the case at Fletcher-Challenge Paper's Boyer mill in Tasmania, a proportion of cold caustic soak (CCS), recycled fibre (RCF) and chemical kraft pulps are added to the thermomechanical pulp (Figure 7.1). This pulp mixture (furnish) then enters the head-box before proceeding to the wet end of the paper machine. At this stage of the process a non-fibrous clay filler is added to the pulp furnish, which serve to fill in spaces between the pulp fibres. Excess water is then removed and the fibres left behind bind together to form a wet web of paper. This wet paper sheet is then pressed and dried to make the final newsprint product at an assumed standard grammage of 45 gsm.

Figure 7.1- Production system summary flow chart showing each stage from the growing forest to the production of timber flitches and newsprint. Symbols in italics refer to names defined in the text.



7.2.2 Defining Incomes and Costs

As incomes and costs occur at different times in the production system, present value analysis was employed to accommodate differences in the timing of costs and returns. A discount rate of 5% was assumed.

The economic methodologies used to describe the production system were:

- *Net Present Value* analysis; and
- *Profitability Index.*

Net Present Value was calculated as the difference of the total of Present-Value income and total value of Present Value costs (Epp and Malone 1981):

$$P_{PV} = I_{PV} - C_{PV} \tag{7.1}$$

where:

- P_{PV} is the expression of present value of profit; and
- I_{PV} and C_{PV} are expressions of present value income and costs respectively.

Profitability Index is essentially the ratio of the present value of profit (P_{PV}) (being total present value income minus total present value costs) and the present value of total costs (see Anthony and Reece 1989) and estimated following:

$$PI = 100.\frac{(I_{PV} - C_{PV})}{C_{PV}} \tag{7.2}$$

where:

- PI is the *Profitability Index.*

"Present" was defined as the time of clearfall harvest (at rotation end, 25 years), and all costs and incomes were appreciated to the time of clearfall using the general formula:

$$PV = V\left(1 + \frac{d}{100}\right)^{(t_{CF} - t_V)} \tag{7.3}$$

where:

- *PV* is the value at the time of clearfall harvest (t_{CF}) at rotation end of a cost or income *V*, occurring prior to rotation end (at time t_V), and *d* is the discount rate.

Income was derived from the sale of timber flitches and newsprint on three occasions throughout the plantation lifespan, being at each of the two thinning operations (T1 and T2 respectively) and at clearfall (CF). Hence present value of income was calculated as:

$$I_{PV} = \sum_{y=T1,T2,CF}\left[\left(IFL_Y + INEWS_Y\right)\left(1+\frac{d}{100}\right)^{(t_{CF}-t_y)}\right] \quad (7.4)$$

where:

- IFL_y and $INEWS_y$ are the incomes derived from sale of timber flitches and newsprint respectively by harvesting operation (y); and
- t_y is the age of harvest operations *T1*, *T2* and *CF* in relation to the time of establishment being year zero.

Similarly, the present value of total costs was derived following:

$$C_{PV} = CGROW_y + \sum_{y=T1,T2,CF}\left[CPROD_y\left(1+\frac{d}{100}\right)^{(t_{CF}-t_y)}\right] \quad (7.5)$$

where:

- $CGROW_y$ is the total growing cost per hectare of plantation at the time of clearfall; and
- $CPROD_y$ is the per-hectare sum of all costs associated with the production of timber flitches and newsprint from standing forest by harvesting operation y.

The cost of production may be split into several major components:

$$CPROD_y = \sum_y\begin{pmatrix}CHARV_y, CTRANS_y, CBARK_y, CSAWN_y,\\ CCHIP_y, CTMP_y, CBLEACH_y, CNEWS_y\end{pmatrix} \quad (7.6)$$

where:

- $CHARV_y$ is the harvesting cost per hectare;
- $CTRANS_y$ is the per hectare cost of transporting logs from the forest to the production mill;

- $CBARK_y$ is the per hectare cost of debarking the delivered green logs;
- $CSAWN_y$ is the per hectare cost of sawing debarked round logs into flitches;
- $CCHIP_y$ is the per hectare cost of chipping debarked round logs on a chipper canter to produce flitches and wood chips for thermomechanical pulping;
- $CTMP_y$ is the per hectare cost of converting flitch mill chips to virgin thermomechanical pulp;
- $CBLEACH_y$ is the per hectare cost of bleaching thermomechanical pulp fibres using a peroxide bleaching system; and
- $CNEWS_y$ is the per hectare cost of converting bleached thermomechanical pulp to 45 gsm newsprint; where
- all costs are represented by harvesting operation, y.

The following sections describe the components of the production system as they were modelled.

7.2.2.1 Growing Costs

The total growing cost of a hectare of plantation forest appreciated to the time of clearfall (*CGROW*) was defined as:

$$CGROW = EST\left(1+\frac{d}{100}\right)^{t_{cf}} + \left(ANNLAND + ANNMAINT\right)\left[\left(1+\frac{d}{100}\right)^{t_{CF}} - 1\right]\left(\frac{100}{d}\right) \qquad (7.7)$$

where:

- *EST* is the per hectare cost of plantation establishment; and
- *ANNLAND* and *ANNMAINT* are the annual per-hectare costs of land use and plantation maintenance respectively.

The growing costs did not include the costs of thinning as these were included as harvesting costs.

7.2.2.2 Harvesting Costs

Harvesting costs per hectare by harvesting operation ($CHARV_y$) were calculated following:

$$CHARV_y = HARVWT_y \times HARVRATE_y \quad (7.8)$$

where:

- $HARVWT_y$ is the per-hectare harvested mass of wood and bark in green tonnes; and
- $HARVRATE_y$ is the harvesting cost per green tonne harvested.

$HARVWT_y$ was calculated as the sum of the total mass of wood ($WMASS_y$) and the total mass of bark ($BMASS_y$):

$$HARVWT_y = WMASS_y + BMASS_y \quad (7.9)$$

Total wood mass was estimated from:

$$WMASS_y = VOLHARV_y \times WGD_y \quad (7.10)$$

where:

- $VOLHARV_y$ is the total under-bark harvested volume in cubic metres per hectare by harvesting operation y; and
- WGD_y is the green density of wood by harvesting operation y.

Green densities for wood volume, by harvesting operation y, were calculated from respective harvest mean basic density and saturation after:

$$WGD_y = \frac{DENS_{yBASE}}{1000} + SAT_y\left(1 - \frac{DENS_{yBASE}}{1000 \times SGW}\right) \quad (7.11)$$

where:

- $DENS_{yBASE}$ is the mean basic density of harvested wood at harvest operation y, expressed in kilograms per cubic metre;
- SAT_y is the mean saturation of harvested wood at harvest operation y, expressed as a fraction (e.g. 0.9); and

- *SGW* is the specific gravity of cell wall material (assumed to be 1.5t/m^3 after Kellogg *et al.* 1975).

Total mass of bark was estimated from:

$$BMASS_y = \frac{VOLHARV_y \times \frac{BRK_{BASE}}{100}}{\left(1 - \frac{BRK_{BASE}}{100}\right) \times BGD} \quad (7.12)$$

where:

- BRK_{BASE} is the percentage of the total harvested volume which is bark; and
- *BGD* is the green density of bark, assumed to be constant across harvesting operation at 0.7 tonnes per cubic meter of bark.

7.2.2.3 Transport Costs

Transport cost per hectare by harvesting operation ($CTRANS_y$) composed of the cost of transporting green logs from the forest plantation to the debarking apparatus outside the flitch and pulp mills. It was calculated as the product of the total green weight transported and the effective cost rate per green tonne transported (*TRANSRATE*). Transported mass was assumed to be equivalent to the total mass of harvested log ($HARVWT_y$), hence the transport cost could be expressed as:

$$TRANSCOST_y = HARVWT_y \times TRANSRATE \quad (7.13)$$

7.2.2.4 Debarking Cost

The cost of debarking green logs delivered from the forest, by harvesting operation was calculated from:

$$CBARK_y = VOLTOTDEL_y \times BARKRATE \quad (7.14)$$

where:

- $VOLTOTDEL_y$ is the total volume of green log in cubic metres per hectare (comprising wood and bark) delivered from the forest for harvesting operation *y*; and
- *BARKRATE* is the cost of debarking a cubic metre of green log.

The total delivered volume of green logs was calculated from:

$$VOLTOTDEL_y = VOLHARV_y + \left(VOLHARV_y \times \frac{\frac{BRK_{BASE}}{100}}{\left(1 - \frac{BRK_{BASE}}{100}\right)} \right) \quad (7.15)$$

7.2.2.5 Sawing Cost

The cost of sawing a cubic metre of debarked green log into rough green flitch (*CSAWN*), by harvesting operation *y*, was estimated from:

$$CSAWN_y = VOLSAWN_y \times SAWNRATE \quad (7.16)$$

where:

- $CSAWN_y$ is the cost of sawing in \$/m^3 of sawn log
- $VOLSAWN_y$ is the volume of harvested wood which is directed to the saw mill (i.e. "saw-log volume"); and
- *SAWNRATE* is the cost of sawing a cubic metre of rough green flitch.

The saw-log volume ($VOLSAWN_y$) was estimated following:

$$VOLSAWN_y = \frac{SAWNFLREC_y}{100} \times VOLHARV_y \quad (7.17)$$

where:

- $SAWNFLREC_y$ is the percentage volume fraction of green logs ($VOLHARV_y$) which is directed to the sawmill by harvesting operation *y* (the current model assumes that $SAWNFLREC_y$ is zero for *y* = T1 and T2 – Figure 8.1).

7.2.2.6 Chipping Cost

The cost of chipping debarked green logs on a log canter (*CCHIP*), by harvesting operation y was estimated from:

$$CCHIP_y = VOLCHIP_y \times CRATE \quad (7.18)$$

where:

- $VOLCHIP_y$ is the volume of harvested wood which is directed to the chipper-canter (i.e. "chipper-canter volume"); and
- *CRATE* is the cost of chipping a cubic metre of green log on a log canter.

The "chipper-canter volume" ($VOLCHIP_y$) was calculated following:

$$VOLCHIP_y = VOLSAWN_y - VOLHARV_y \quad (7.19)$$

7.2.2.7 Income from sale timber flitches

The production system defined here (see Figure 7.1) utilises the harvested wood volume in different ways depending on the harvesting operation. A proportion of green logs at clearfall harvest are considered of sufficient size and quality to saw into flitches as opposed to the chip canter method used solely in harvesting operations T1 and T2 (Figure 7.1). The sawing process is considered to be a more profitable way of producing flitches.

The total income derived from the sale of timber flitch (IFL_y) by harvesting operation y was estimated from:

$$IFL_y = ISAWNFL_y + ICHIPFL_y \quad (7.20)$$

where:

- $ISAWNFL_y$ is the income derived from the sale of sawn flitch; and
- $ICHIPFL_y$ is the income derived from the sale of flitch produced on a chipper-canter.

The income derived from sale of sawn flitches by harvesting operation y ($ISAWNFL_y$) was calculated as the product of the volume of sawn flitch produced ($VOLSAWNFL_y$) and the average value (income rate) of a cubic metre of rough-green sawn cantered flitch (*IRSAWNFL*):

$$ISAWNFL_y = VOLSAWNFL_y \times IRSAWNFL \quad (7.21)$$

The volume of sawn flitch produced was estimated from:

$$VOLSAWNFL_y = \left(1 - \frac{SAWNLOSS}{100}\right) \times VOLSAWN_y \quad (7.22)$$

where:

- *SAWNLOSS* is the percentage fraction of saw-log volume that is lost as sawdust

The income derived from sale of flitches produced from the chipper-canter, by harvesting operation y ($ICHIPFL_y$) was calculated as the product of the volume of flitch produced from the chipper-canter ($VOLCHIPFL_y$) and the average value (income rate) of a cubic metre of rough-green chip cantered flitch (*IRCHIPFL*):

$$ICHIPFL_y = VOLCHIPFL_y \times IRCHIPFL \quad (7.23)$$

The volume of flitch produced from the chipper-canter by harvesting operation y was estimated from:

$$VOLCHIPFL_y = \frac{CHIPFLREC_y}{100} \times \left(VOLHARV_y - VOLSAWNFL_y\right) \quad (7.24)$$

where:

- *CHIPFLREC* is the percentage volume fraction that is recovered as rough green chipped flitch.

7.2.2.8 Pulping Costs

The total volume of chips in cubic metres per hectare available to thermomechanical pulp (*TMP*) by harvesting operation y ($VOLTMPCHIP_y$) was calculated as:

$$VOLTMPCHIP_y = \left(VOLCHIP_y - VOLCHIPFL_y\right) \times \left(1 - \frac{CHIPLOSS}{100}\right) \quad (7.25)$$

where:

- $VOLCHIP_y$ is the volume of harvested and debarked wood which is directed to the chipper-canter (i.e. the volume of debarked harvested wood which is not sawn);

- $VOLCHIPFL_y$ is the volume of rough green chip-cantered flitch produced from $VOLCHIP_y$; and
- $CHIPLOSS$ is the percentage volume fraction of green log that is lost as chipper waste.

To convert the volume prediction of wood-chips entering the TMP mill into a prediction of wood-chip mass:

$$MASSTMPCHIP_y = \frac{PWDEN_{BASEy}}{1000} \times VOLTMPCHIP_y \quad (7.26)$$

where:

- $MASSTMPCHIP_y$ is the oven dry tonnes of wood chips entering the TMP mill; and
- $PWDEN_{BASEy}$ is the assumed mean basic density of wood chips entering the TMP mill by harvesting operation y, expressed in kilograms per cubic metre.

The OD mass of thermomechanical pulp produced ($MASSTMP$) by harvesting operation, y, was calculated following:

$$MASSTMP_y = \left(\frac{TMPREC}{100}\right) \times MASSTMPCHIPS_y \quad (7.27)$$

where:

- $TMPREC$ is the percentage OD mass of wood chips converted to bleached thermomechanical pulp.

The cost of pulping (converting wood chips to unbleached thermomechanical pulp) by harvesting operation was ultimately calculated as:

$$CTMP_y = MASSTMP_y \times TMPRATE_y \quad (7.28)$$

where:

- $CTMP_y$ is the cost of thermomechanical pulping (i.e. converting wood chips to TMP); and
- $TMPRATE_y$ is the cost of producing an OD tonne of TMP by harvesting operation y.

The *TMPRATE* was assumed to vary according to changes in both the operational and capital costs of refining at each harvesting operation following:

$$TMPRATE_y = (SEC_y \times POWER) + (SEC_y \times TMPCAPRATE) \quad (7.29)$$

where:

- SEC_y is the specific energy required to thermomechanically refine an oven dry tonne of pulp by harvesting operation y, defined in kilo-watt hours per OD tonne; and
- *POWER* is the cost of electrical power per kilo-watt hour; and
- *TMPCAPRATE* is the capital cost of thermomechanical refining (defined in terms of per kilo-watt hour of power consumed).

7.2.2.9 Bleaching Costs

The bleaching of virgin TMP fibres was assumed to be based on the use of a peroxide bleaching system to achieve a high brightness newsprint paper grade.

The cost of bleaching (*CBLEACH*) by harvesting operation y was estimated following:

$$CBLEACH_y = MASSTMP_y \times BLEACHRATE \quad (7.30)$$

where:

- *BLEACHRATE* is the cost of bleaching an OD tonne of TMP, comprising the cost of stock preparation, hydrogen peroxide addition, sodium hydroxide addition, the addition of various other miscellaneous chemicals and capital, expressed per OD tonne of TMP bleached.

Hence:

$$BLEACHRATE = \sum(STORATE, PERRATE, CAURATE, MCRATE) \quad (7.31)$$

where:

- *STORATE* is the cost of preparing the bleaching chemical stock per oven dry tonne of TMP, assumed fixed;
- *PERRATE* is the cost of hydrogen peroxide per oven dry tonne of TMP;

- *CAURATE* is the cost of sodium hydroxide (caustic) per oven dry tonne of TMP; and

- *MCRATE* is the cost of other miscellaneous chemicals required by the defined bleaching process, assumed fixed.

The cost of hydrogen peroxide depends on the amount of it required to be added to the bleaching process, after:

$$PERRATE = \left(\frac{PER}{100} \times PERTONRATE\right) + \left(\frac{PER}{100} \times PERCAPRATE\right) \quad (7.32)$$

where:

- *PERTONRATE* is the cost of hydrogen peroxide per tonne;

- *PERCAPRATE* is the capital cost of bleaching with hydrogen peroxide per tonne of hydrogen peroxide used; and

- *PER* is the amount of hydrogen peroxide required to bleach the TMP to a desired level of sheet brightness, expressed as a percentage per oven dry tonne of pulp produced calculated as (following Chapter 4):

$$PER = \frac{\left(PB_{REQ} - PB_{BASE}\right)}{4.10} \quad (7.33)$$

where:

- PB_{REQ} is the desired ISO brightness, expressed in percentage units at 457nm, of the final newsprint sheet; and

- PB_{BASE} is the ISO brightness of the pulp furnish prior to the addition of *PER*, estimated from handsheets and expressed in percentage units at 457nm.

Similarly, the cost of sodium hydroxide (caustic) was estimated from:

$$CAURATE = \left(\frac{CAU}{100} \times CAUTONRATE\right) + \left(\frac{CAU}{100} \times CAUCAPRATE\right) \quad (7.34)$$

where:

- *CAUTONRATE* is the cost of sodium hydroxide (caustic) per tonne;

- *CAUCAPRATE* is the capital cost of bleaching with sodium hydroxide per tonne of sodium hydroxide used; and
- *CAU* is the amount of sodium hydroxide to be added in conjunction with the hydrogen peroxide to maintain optimum bleaching conditions, in tonnes, calculated as (following Chapter 4):

$$CAU = 0.05 + (0.77 \times PER) \tag{7.35}$$

7.2.2.10 Newsprint Production Costs

As previously described, a proportion of cold caustic soak (CCS), recycled fibre (RCF) and chemical kraft pulps (KRA) are added to the TMP to produce high brightness newsprint. This pulp mixture (furnish) then enters the head-box before proceeding to the wet end of the paper machine, where a clay filler (FIL) is added to the pulp furnish to improve the optical properties of the final newsprint sheet. It is assumed that all pulp other than the TMP is produced outside the current defined production system. The costs of CCS, RCF and KRA pulps may then be treated as either the current market purchase price or the cost of producing each pulp respectively.

The cost per hectare of converting peroxide bleached TMP into high brightness newsprint by harvesting operation y was estimated from:

$$CNEWS_y = (MASSNEWS_y \times NEWSRATE) + CCOM_y \tag{7.36}$$

where:

- $CNEWS_y$ is the per hectare cost of high brightness newsprint production;
- $MASSNEWS_y$ is the oven dry tonnes of newsprint produced per hectare of forest planted;
- $CCOM_y$ is the per hectare cost of adding cold caustic soak ($CCCS_y$), recycled fibre ($CRCF_y$) and chemical kraft ($CKRA_y$) pulp to the TMP and clay filler ($CFIL_y$) to the forming newsprint sheet; and
- $NEWSRATE_y$ is the cost of producing an OD tonne of newsprint.

Hence:

$$CCOM_y = CCCS_y + CRCF_y + CKRA_y + CFIL_y \tag{7.37}$$

The cost per hectare of adding CCS to the pulp furnish for newsprint production by harvesting operation y was calculated as the product of the mass of CCS added (expressed in OD tonnes) and the unit cost of CCS per OD tonne:

$$CCCS_y = \left(\frac{\%CCS}{100} \times \left(MASSTMP_y \times \frac{100}{\%TMP}\right)\right) \times CCSRATE \qquad (7.38)$$

where:

- *%CCS* is the fraction of the total OD mass of pulp furnish which is *CCS*, expressed in percentage points;
- *%TMP* is the fraction of the total OD mass of pulp furnish which is *TMP*, expressed in percentage points; and
- *CCSRATE* is the cost of *CCS* per OD tonne.

The cost per hectare of adding RCF to the pulp furnish for newsprint production (*RCFCOST*) by harvesting operation y was calculated as the product of the mass of RCF added (expressed in OD tonnes) and the unit cost of RCF per OD tonne:

$$CRCF_y = \left(\frac{\%RCF}{100} \times \left(MASSTMP \times \frac{100}{\%TMP}\right)\right) \times RCFRATE \qquad (7.39)$$

where:

- *%RCF* is the percentage OD mass of RCF added to the total OD mass of pulp furnish, assumed fixed; and
- *RCFRATE* is the cost of RCF per OD tonne.

The cost per hectare of adding KRA to the pulp furnish for newsprint production (*KRACOST*) by harvesting operation y was calculated as the product of the mass of KRA added (expressed in OD tonnes) and the unit cost of KRA per OD tonne:

$$CKRA_y = \left(\frac{\%KRA}{100} \times \left(MASSTMP \times \frac{100}{\%TMP}\right)\right) \times KRARATE \qquad (7.40)$$

where:

- *%KRA* is the percentage OD mass of KRA added to the total OD mass of pulp furnish; and
- *KRARATE* is the cost of KRA per OD tonne.

Kraft pulp is added to the pulp furnish to improve the strength properties of the final newsprint sheet. The relationship between newsprint strength and the intrinsic strength properties of the pulp furnish is assumed to vary solely with variation in the properties of TMP in the furnish. Thus to achieve a desired level of newsprint strength, the amount of kraft pulp added to the furnish must vary depending on the intrinsic strength properties of the TMP in the furnish. The percentage of kraft added on top of the fixed percentages of TMP, CCS and RCF was estimated after:

$$\%KRA = 2.74\left(TE_{REQ} - TE_{BASEy}\right) + 0.664\left(TN_{REQ} - TN_{BASEy}\right) \quad (7.41)$$

where:

- TE_{REQ} is the desired tear strength, measured in milli-Newton-metres squared per gram, of the final newsprint sheet;
- TE_{BASEy} is the tear strength of the pulp furnish prior to the addition of kraft pulp, by harvesting operation y, estimated from handsheets and expressed as milli-Newton-metres squared per gram;
- TN_{REQ} is the desired tensile strength, measured in Newton-metres per gram, of the final newsprint sheet; and
- TN_{BASEy} is the tensile strength of the pulp furnish prior to the addition of kraft pulp, by harvesting operation y, estimated from handsheets and expressed in Newton-metres per gram.

The cost per hectare of adding clay filler (*FIL*) to the forming newsprint (*FILCOST*) by harvesting operation y was calculated as the product of the mass of FIL added to the forming sheet (expressed in OD tonnes) and the unit cost of FIL per OD tonne:

$$FILCOST = \left(\frac{\%FIL}{100} \times \left(MASSTMP \times \frac{100}{\%TMP}\right)\right) \times FILRATE \quad (7.42)$$

where:

- *%FIL* is the percentage OD mass of FIL added to the forming newsprint; and
- *FILRATE* is the cost of FIL per OD tonne.

Clay filler is added to the forming newsprint to improve the optical properties, namely to increase the opacity of the final sheet. The relationship between newsprint opacity and the intrinsic optical properties of the pulp furnish is assumed to be dependent solely on the optical properties of TMP in the furnish. Thus to achieve a desired newsprint opacity, the amount of clay filler added to the furnish must vary depending on the intrinsic optical properties of the TMP in the furnish. The percentage of filler added to the forming newsprint sheet was estimated following (see Chapter 4):

$$\%FIL = \frac{\left(OP_{REQ} - OP_{BASE}\right)}{1.25} \tag{7.43}$$

where:

- OP_{REQ} is the desired opacity, expressed as the percentage reflectance, of the final newsprint sheet; and
- OP_{BASE} is the opacity of the pulp furnish prior to the addition of FIL, estimated from handsheets and expressed in units of percentage reflectance.

The mass of final newsprint in OD tonnes was calculated after:

$$MASSNEWS_y = \frac{NEWSREC}{100} \times \left(MASSFIL_y + MASSFURN_y\right) \tag{7.44}$$

where:

- $NEWSREC$ is the percentage OD mass of pulp furnish (i.e. TMP, CCS, RCF and KRA) that is recovered as newsprint;
- $MASSFIL_y$ is the OD mass of FIL added to the forming newsprint; and
- $MASSFURN_y$ is the OD mass of blended TMP, CCS, RCF and KRA pulp.

Hence, the total mass of pulp furnish is the sum of the mass of CCS, TMP, RCF and KRA pulps entering the paper-machine head-box:

$$MASSFURN_y = \sum_y \left(MASSTMP_y, MASSCCS_y, MASSRCF_y, MASSKRA_y\right) \tag{7.45}$$

7.2.2.11 Income from sale of Newsprint

The income derived from the sale of high brightness newsprint (*INEWS*) by harvesting operation y was calculated after:

$$INEWS_y = MASSNEWS_y \times IRNEWS \quad (7.46)$$

where:

- $MASSNEWS_y$ is the mass of newsprint produced, in OD tonnes; and
- *IRNEWS* is the value of an OD tonne of finished newsprint.

The mass of newsprint produced by harvesting operation was estimated from:

$$MASSNEWS_y = \frac{NEWSREC}{100} \times \left(MASSFIL_y + MASSFURN_y\right) \quad (7.47)$$

where:

- *NEWSREC* is the percentage OD mass of pulp furnish (i.e. TMP, CCS, RCF and KRA) that is recovered as newsprint;
- $MASSFIL_y$ is the OD mass of FIL added to the forming newsprint; and
- $MASSFURN_y$ is the OD mass of blended TMP, CCS, RCF and KRA pulp.

7.2.3 Simulation of the model

A simulation model of the production system was constructed using Excel 97 spreadsheet software (Microsoft 1997) following the methods of Chambers and Borralho (1999) and Greaves (1999). Starting values as shown in Tables (7.1) and (7.2) were assumed for the numerous parameters defining the production system. These generic parameters were based on advice given by John Simpson[1] (pers. comm.) and Peter Sylvester[2] (pers. comm.) and may be considered appropriate as a general description of a local vertically integrated forestry company in South-eastern Australia.

John Simpson, Forest Manager, Fletcher Challenge Paper Boyer Mill

[2] Peter Sylvester, Managing Accountant, Fletcher Challenge Paper Boyer Mill

Table 7.1- Assumed production system parameters across harvesting operations

Parameter	Description	Units	Assumed Value
EST	plantation establishment cost	$/ha	1600
ANNLAND	annual cost of land use	$/ha	120
ANNMAINT	annual plantation maintenance cost	$/ha	120
d	annual discount rate	%	5
TRANSRATE	cost of green log transport	$/green tonne	10
BARKRATE	cost of debarking	$/m^3 delivered	10
CRATE	cost of chipping on a log canter	$/m^3 chip logs	70
IRCHIPFL	value of chip cantered flitch	$/m^3 chip. flitch	230
CHIPLOSS	chip-canter loss to waste	%	3
TMPREC	OD mass of chips converted to TMP	%	90
POWER	cost of electrical power to operate refiners	$/kWhr	0.05
TMPCAPRATE	capital costs from operating refiners	$/kWhr	0.05
STORATE	cost (fixed and variable) of chemical stock preparation	$/ODt TMP	25
MCRATE	cost (fixed and variable) of other miscellaneous chemicals	$/ODt TMP	60
PERTONRATE	cost of peroxide used for bleaching	$/t PER	900
PERCAPRATE	capital costs of bleaching with peroxide	$/t PER	900
PER	mass of peroxide used for bleaching	t/ODt TMP	4.90
CAU	mass of caustic used for bleaching	t/ODt TMP	3.82
CAUTONRATE	cost of caustic used for bleaching	$/t CAU	850
CAUCAPRATE	capital costs associated with adding caustic	$/t CAU	850
%TMP	OD mass of *TMP* in pulp furnish	%	60
%CCS	OD mass of *CCS* in pulp furnish	%	25
%RCF	OD mass of *RCF* in pulp furnish	%	15
CCSRATE	cost of cold caustic soak pulp	$/ODt CCS	400
RCFRATE	cost of recycled fibre	$/ODt RCF	450
KRARATE	cost of chemical *KRAFT* pulp	$/ODt KRA	800
FILRATE	cost of clay *FILLER*	$/tonne *FILLER*	800
NEWSRATE	cost of producing newsprint	$/ODt NEWS	80
NEWSREC	paper mill recovery	%	90
IRNEWS	value of newsprint	$/ODt NEWS	960

Table 7.2- Assumed production system parameters: parameters specific to harvesting operation.

Parameter	Description	Units	Assumed Value		
			T1	T2	CF
t	time of harvesting operation	years	15	20	25
VOLHARV	total harvestable volume (under bark)	m^3/ha	100	120	400
HARVRATE	cost of harvesting	$/green tonne	19	16	14
SAWNFLREC	sawmill recovery of rough green sawn flitch	%	0	0	20
CHIPFLREC	chip canter recovery of green chipped flitch	%	0	15	15
IRSAWNFL	value of sawn flitch	$/$m^3$ sawn flitch	n/a	n/a	230
SAWNLOSS	sawmill loss to waste	%	n/a	n/a	5
SAWNRATE	cost of sawing flitches	$/$m^3$ saw-log vol.	n/a	n/a	50

Estimates of stand basic density and pulpwood basic density (Table 7.3) were derived from data presented by Cown (1992), predictions using the STANDQUO computer software package (Tian and Cown 1997) and local knowledge (John Simpson *pers. comm.*). Estimates of green-wood saturation (*SAT*) were derived from heartwood-fraction predictions after Cown and McConchie (1982); assumed sapwood saturation of 94% (after data presented by Kininmonth 1991); and assumed heartwood saturation of 23% based on data presented by Maddern-Harris and Cown (1991).

Table 7.3- Production system parameters: wood properties by harvesting operation (see text for information source).

Parameter	Description	Units	Value		
			T1	T2	CF
DEN	basic density of harvested wood	kg/m^3	380	420	450
SAT	saturation of harvested wood	%	90	88	85
BGD	green density of the harvested bark	t/m^3	0.7	0.7	0.7
PWDEN	basic density of pulp mill wood chips	kg/m^3	380	440	480
BARK	percentage of total log mass which is bark	%	8	8	8

Starting values for thermomechanical pulp properties (Table 7.4) were based on unpublished pulp property assessments carried out by Fletcher Challenge Paper

(formerly Australian Newsprint Mills) at their Boyer mill and from local advice (Paul Banham[3] *pers. comm.*).

Table 7.4- Assumed production system parameters: newsprint and TMP properties by harvesting operation (see text for information source).

Parameter	Description	Units	Value		
			T1	T2	CF
SEC_y	specific refining energy consumption	kWhr	2523	2329	2200
TE_{REQ}	desired tear strength of newsprint	mNm^2/g	9.0	9.0	9.0
TE_{BASEy}	tear strength of TMP handsheet	mNm^2/g	7.0	7.9	8.5
TN_{REQ}	desired tensile strength of newsprint	Nm/g	42.0	42.0	42.0
TN_{BASEy}	tensile strength of TMP handsheet	Nm/g	36.3	35.5	35.0
BRG_{REQ}	desired ISO brightness of newsprint	%	80.0	80.0	80.0
BRG_{BASE}	ISO brightness of TMP handsheet	%	59.9	59.9	59.9
OP_{REQ}	desired opacity of newsprint	%	90.0	90.0	90.0
OP_{BASE}	opacity of TMP handsheet	%	82.9	82.9	82.9

7.2.4 Sensitivity Analysis

Spearman's Rank Order Correlation (Palisade 1997) was used to determine the production system input parameters having the greatest influence on the estimated *Profitability Index*. Monte-Carlo simulation was used to generate 10,000 production system input parameter sets (see also Chapter 4). All production system inputs were allowed to vary by ±20% with an assumed triangular distribution following the procedure of Greaves (1999).

This allowed all input assumptions to be compared over a constant range of variation. Whilst the certainties associated with the assumed values of each input parameter may vary, the realm of assigning separate standard errors (ranges of allowable variation) to each input parameter introduces another level of complexity to the analysis, with its own assumptions and issues of confidentiality. Ultimately, the results of the sensitivity analysis reflect the constraints imposed upon input parameters by this arbitrary allowable variation (±20%), but were used simply to indicate the first parameters which needed clarifying in subsequent modeling efforts.

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[3] Paul Banham, Research Scientist, Fletcher Challenge Paper Boyer Mill

Simulations were generated and rank order correlations estimated using the @RISK software (Palisade 1997), and the statistical significance of correlation coefficients predicted using the CORR procedure in SAS (SAS Institute Inc. 1993).

7.3 Results

7.3.1 Enterprise wood-flows, incomes and costs

The calculated wood and wood product flows within the enterprise are presented in Table (7.5) on the following page. Calculated costs and incomes (from the base assumptions outlined previously in Section 7.2.3) are presented in Table (7.6).

Table 7.5- Estimated wood and product flows by harvesting operation and total.

wood flow (per hectare)		T1	T2	CF	TOTAL	unit
delivered volume (incl. bark)	*VOLTOTDEL*	108.7	130.4	434.8	673.9	m3/ha
bark volume	*VOLBARK*	8.7	10.4	34.8	53.9	m3/ha
havested volume (under bark)	*VOLHARV*	100.0	120.0	400.0	620.0	m3/ha
chipped flitch volume	*VOLCHIPFL*	0.0	18.0	48.0	66.0	m3/ha
sawn flitch volume	*VOLSAWNFL*	n/a	n/a	80.0	80.0	m3/ha
pulp chip volume	*VOLTMPCHIP*	100.0	98.9	263.8	462.8	m3/ha
thermo-mechanical pulp mass	*MASSTMP*	34.2	39.2	114.0	187.4	ODt/ha
cold caustic soak pulp mass	*MASSCCS*	14.3	16.3	47.5	78.1	ODt/ha
recycled fibre pulp mass	*MASSRCF*	8.6	9.8	28.5	46.8	ODt/ha
chemical kraft pulp mass	*MASSKRA*	5.2	4.8	11.6	21.6	ODt/ha
pulp furnish mass	*MASSFURNISH*	62.2	70.1	201.5	333.9	ODt/ha
clay filler mass	*MASSFIL*	3.5	4.0	11.4	18.9	ODt/ha
newsprint furnish mass*		65.8	74.1	212.9	352.8	ODt/ha
newsprint	*MASSNEWS*	59.2	66.7	191.7	317.5	ODt/ha
newsprint (area)	*AREANEWS*	1.32	1.48	4.26	7.06	m^2 ($x10^6$)

* newsprint furnish mass is equal to the sum of the mass of pulp furnish (*MASSFURNISH*) and clay filler (*MASSFIL*).

Table (7.5) shows that of the total harvested under-bark (merchantable) wood volume (620 m^3/ha) only 23.5% become rough green flitches, while 76.5% is

thermomechanically pulped to produce around 318 OD tonnes of newsprint (approximately 7.1 million square metres of 45gsm newsprint). Of the total flitch volume (*VOLCHIPFL+VOLSAWNFL*), 45% is produced from the chipper canter at harvesting operations T2 and clearfall, and 55% from sawing at clearfall. Added to the 187 OD tonnes (per hectare) of thermomechanical pulp (*TMP*) produced, were 78 OD tonnes of cold caustic soak (*CCS*) pulp, 47 OD tonnes of recycled fibre (*RCF*) pulp and 22 OD tonnes of chemical *KRAFT* pulp, giving a total pulp furnish mass of 334 OD tonnes per hectare (Table 7.5). In addition, a total of around 19 OD tonnes per hectare of *FILLER* was added to the forming newsprint sheet on the paper machine. This resulted in a total newsprint furnish mass of 353 OD tonnes (Table 7.5).

Table 7.6- Estimated enterprise costs and incomes (per hectare) by harvesting operation (T1, T2, CF), total Present Value of costs and incomes at the time of clearfall harvest (*PV* is 25 years), *Net Present Value* of profit at the time of clearfall harvest (P_{PV}), Present Value of total incomes and costs at clearfall harvest (I_{PV} and C_{PV} respectively), and *Profitability Index* (*PI* - following Equation 7.2).

Cost, Income			Harvesting Operation			TOTAL
			T1	T2	CF	
growing cost	*CGROW*	$/ha	n/a	n/a	n/a	$16,873
harvesting cost	*CHARV*	$/ha	$3,444	$2,731	$6,193	$12,368
transport cost	*CTRANS*	$/ha	$1,813	$1,707	$4,423	$7,943
delivered log cost*		$/ha	$5,257	$4,438	$10,616	$37,184
debarking cost	*CBARK*	$/ha	$1,771	$1,665	$4,348	$7,783
sawing cost	*CSAWN*	$/ha	n/a	n/a	$4,400	$4,400
chipping cost	*CCHIP*	$/ha	$11,402	$10,721	$22,400	$44,523
log processing cost**		$/ha	$13,173	$12,385	$31,148	$56,706
pulping cost	*CPULP*	$/ha	$14,052	$11,646	$25,075	$50,774
bleaching cost	*CBLEACH*	$/ha	$13,273	$11,915	$27,157	$52,345
pulp mill cost***		$/ha	$27,326	$23,561	$52,233	$103,119
newsprint cost****	*CNEWS*	$/ha	$34,693	$29,708	$65,538	$129,939
total cost	C_{PV}	**$/ha**				**$326,948**
flitch income	*IFLITCH*	$/ha	$0	$5,284	$28,520	$33,804
newsprint income	*INEWS*	$/ha	$92,561	$81,666	$183,987	$358,214
total income	I_{PV}	**$/ha**				**$392,018**
profit	P_{PV}	**$/ha**				**$65,070**
profitability index	*PI*	**%**				**19.9%**

* Delivered log costs include the cost of growing, harvesting and transporting green logs from the forest;
** Log processing costs include the cost of debarking, sawing and chipping (on a log canter)delivered logs;
*** Pulp mill costs include the costs of refining and bleaching the OD mass of TMP; and
**** Newsprint costs include the costs of CCS, RCF and KRA pulp, clay filler and the fixed and variable costs associated with converting the pulp furnish into newsprint.

The production enterprise, as modelled here, is profitable (Table 7.6). *Net Present Value* (or profit) was shown to be $65,070 per hectare of forest plantation (where present value was taken at rotation age - 25 years). The *Profitability Index* (representing the income returned over the costs incurred) was 19.9%. This figure is in the range of acceptability for the case of a vertically integrated forestry enterprise (Greaves, pers. comm.).

The total cost of growing a hectare of unpruned radiata pine to clearfall harvest at age 25 years is $16,873, equating to 5.5% of the total costs (C_{PV}). Delivered cost (i.e. the cost to grow, harvest and transport) equates to around 11% of total costs, or $37,184 per hectare. The cost of debarking, chipping and sawing (termed "log processing cost" in Table 8.6) is 17% of total costs, and pulping and newsprint costs equate to 32% and 40% of the total costs respectively. Figures (7.2) and (7.3) represent a graphical breakdown of the total present value costs and incomes respectively.

Figure 7.2- Major components of total Present Value costs across all harvesting operations, assuming a discount rate (*d*) of 5%.

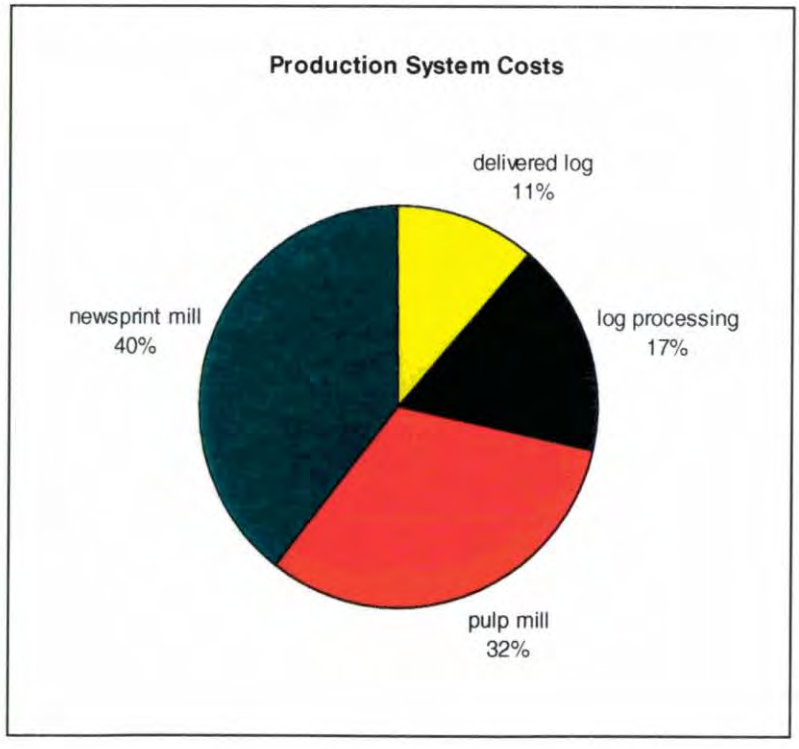
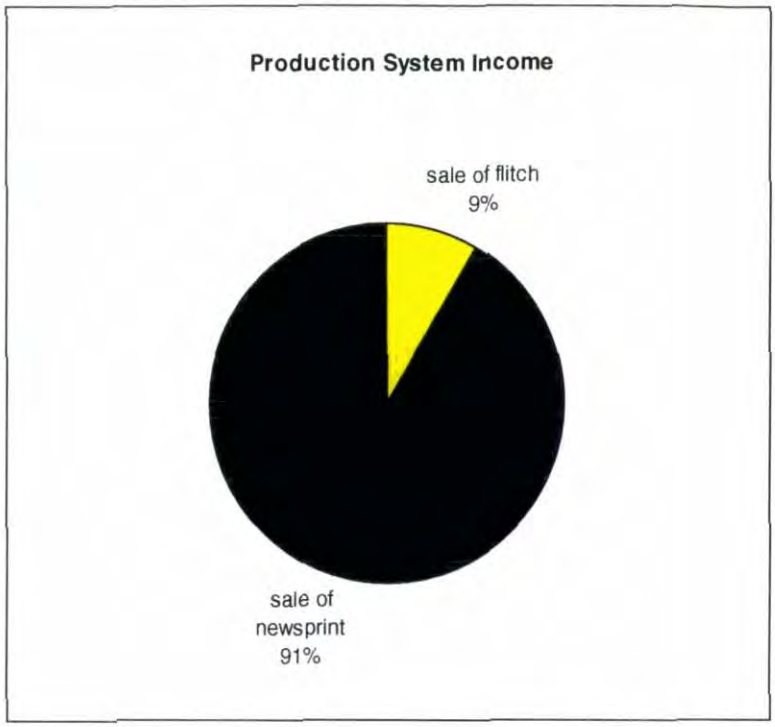


Figure 7.3- Major components of total Present Value incomes across all harvesting operations, assuming a discount rate (*d*) of 5%.



The present value cost of producing an OD tonne of thermomechanical pulp (*CPULP*) comprised approximately equivalent refining and bleaching cost sub-components. Present value newsprint costs (*CNEWS*) were made up mainly from the cost of *CCS* pulp fibre (28%) and the cost of converting the newsprint furnish (i.e. *MASSFURNISH* plus *MASSFILLER*) into newsprint (i.e. *MASSNEWS*) (22%). The "log processing" cost defined in Table (7.6) was assumed to include the costs of debarking, chipping and sawing as described. Of this cost, debarking and sawing made up only around 18% of the overall "log processing" cost, with the majority of this cost (82%) incurred from operating the chipper canter.

The *Profitability Index* (*PI*) may also be calculated for the flitch and newsprint production components separately. This provides an idea of which of the two components is the most profitable. The *PI* of the flitch and newsprint production components of the enterprise were calculated by apportioning the growing, harvesting, transport, debarking and chipping costs to the respective components on the basis of volume used. As 76.5% of the total volume harvested is pulped, 76.5% of growing, harvesting and transport costs were apportioned to the pulping/newsprint component. 76.5% of the costs of debarking and chipping are again attributable to the pulping cost component, however the sawing costs are

solely attributable (100%) to the flitch component. The estimated *Profitability Index* of the flitch and pulping/newsprint components of the enterprise are shown with the breakdown of total attributable costs in Table (7.7).

Table 7.7- Portioning of Present Value costs into either costs associated with flitch production or pulp/newsprint production. Growing, harvesting, transporting, debarking and chip-cantering costs are allocated according to volume. The allocation to flitch is on the basis of *VOLCCFL* and *VOLSAWNFL* excluding wood chip volume (*VOLPCHIPS*) and the allocation to pulp/newsprint production is on the basis of *VOLPCHIPS*. PV was assumed at the time of clearfall harvest (25 years)

Cost, Income			TOTAL	Flitches Fraction of Cost/Income		Newsprint Fraction of Cost/Income	
growing cost	*CGROW*	$/ha	$16,873	23.5%	$3,973	76.5%	$12,908
harvesting cost	*CHARV*	$/ha	$12,368	23.5%	$2,906	76.5%	$9,462
transport cost	*CTRANS*	$/ha	$7,943	23.5%	$1,867	76.5%	$6,076
debarking cost	*CBARK*	$/ha	$7,783	23.5%	$1,829	76.5%	$5,954
sawing cost	*CSAWN*	$/ha	$4,400	100.0%	$4,400	0.0%	$0
chipping cost	*CCHIP*	$/ha	$44,523	23.5%	$10,463	76.5%	$34,060
pulping cost	*CPULP*	$/ha	$50,774	0.0%	$0	100.0%	$50,774
bleaching cost	*CBLEACH*	$/ha	$52,345	0.0%	$0	100.0%	$52,345
newsprint cost	*CNEWS*	$/ha	$129,939	0.0%	$0	100.0%	$129,939
total cost	C_{PV}	$/ha	$326,948		$25,438		$301,518
flitch income	*IFLITCH*	$/ha	$33,804	100.0%	$33,804	0.0%	$0
newsprint income	*INEWS*	$/ha	$358,214	0.0%	$0	100.0%	$358,214
total income	I_{PV}	$/ha	$392,018		$33,804		$358,214
profit	P_{PV}	$/ha	$65,070		$8,366		$56,696
profitability index	*PI*	%	19.9%		32.9%		18.8%

Table (7.7) shows that the *Profitability Index* of the flitch production and pulp/newsprint production components of the enterprise are 32.9% and 18.8% respectively. Although highly profitable, due to less than 24% of the total merchantable wood volume being used to produce flitch (Table 7.5), the total *PI* is being driven by the poorer profitability of newsprint production (18.8% - Table 7.7). It is important to note, however, that the *PI* of the flitch component of the business is dependent upon the existence of the pulp and paper component to utilise the sub-flitch grade logs.

7.3.2 Sensitivity Analysis

Base *Profitability Index* for the enterprise was estimated to be 19% (Table 7.6). The ten input parameters with which *Profitability Index* is most sensitive are presented in Table (7.8). The reported Spearman Rank Order Correlations represent the

strength of the influence that the listed parameter has on *Profitability Index* given the assumed allowable variation in each input parameter of ±20%.

Table 7.8- Sensitivity analysis for *Profitability Index*: Spearman's Rank Order Correlation between the base *Profitability Index* (Eqn 7.2) and the ten most correlated production system input parameters (all presented correlation coefficients are significantly different to zero at p=0.0001), and the expected absolute percentage change in *Profitability Index* resulting from a one percent change in each parameter.

Correlated production system input parameter	Description	Rank Order Correlation	Absolute ΔPI (from the base 19%) per % Δ input parameter
IRNEWS	value of newsprint ($/ODt)	0.71	0.66
SEC	specific energy consumption during refining (kWhr/t)	-0.21	-0.28
TMPREC	TMP mill recovery (%)	0.16	0.21
NEWSREC	newsprint mill recovery (%)	0.13	0.16
PER CONSTANT	the model parameter in Equation (7.31): **"4.10"**	0.12	0.14
NEWSRATE	cost of newsprint (per OD tonne produced)	-0.12	-0.14
IRSAWNFLITCH	value of sawn flitch ($/m^3)	0.12	0.13
POWER	cost of electrical power	-0.11	-0.13
%CCS	the portion of pulp furnish which is CCS pulp (%)	0.10	0.11
d	discount rate	0.10	0.11

The input parameter to which *Profitability Index* is most sensitive is the value of newsprint (*IRNEWS* – expressed in dollars per OD tonne of newsprint sold). Changing *IRNEWS* by the allowable sensitivity range (by ±20%) changes *Profitability Index* by ±0.66%. The second most sensitive input parameter was shown to be the energy consumed during thermomechanical refining; changes in *SEC* changes *PI* by ±0.28%. The ratio of the mass of TMP produced from the mass of wood chips being refined (*TMPREC*) and the ratio of newsprint mass from the oven dry mass of pulp furnish entering the paper machine head box (*NEWSREC*) were also shown to be sensitive parameters determining the profitability of the production enterprise (Table 7.8). However, it is likely that both of these parameters would be estimable with better than ±20% variation. Indeed, the conversion of wood chips to TMP and subsequent conversion of TMP to newsprint seems to be relatively constant across a range of different operating conditions aimed at producing a variety of paper products (Smook 1992). The fifth most sensitive parameter was shown to be a model parameter from Equation (7.31). Again, due to the nature of this parameter (i.e. the denominator in an equation determining the percentage of hydrogen

peroxide bleach required per tonne of TMP entering the bleaching towers), a variation of 20% may be too large a range of sensitivity to allow.

7.4 Discussion

The assumed enterprise as modeled from Equations (7.1) to (7.45) is profitable (Table 8.6) with net profits being 19.9% of net costs. The majority of the under-bark (merchantable) wood volume is used to produce thermomechanical pulp (77% by volume) with less than one quarter sold as rough green timber flitch (after Table 7.7). The income derived from producing newsprint exceeded the income derived from the production of timber flitches by approximately ten times (Figure 7.3) largely reflecting the relative production levels of each product. By apportioning the growing, harvesting, debarking and chipping costs to the flitch production and newsprint production components (on the basis of the relative fraction of total volume used in the respective processes) the *Profitability Index* of the flitch production line is estimated to be a much more profitable 32.9% compared with 18.8% for the newsprint production line (Table 7.7). However, the *Profitability Index* of the flitch component of the business is dependent upon the existence of the newsprint component to utilise the sub-flitch grade logs.

The economic consequences of the current enterprise model would appear to correlate well with reality. The model is assumed to loosely follow the situation of an enterprise traditionally aimed solely toward the production of newsprint for profit. A recent addition to the production of newsprint has been the production of flitch to be sold to a nearby saw mill. Under this scenario one would expect both components of the enterprise to be acceptably profitable. This compares with the sawn timber and liner-board enterprise of Greaves (*in review*), which shows the saw-milling product line to be extremely profitable but the pulp/liner-board line to be making a small loss.

The most sensitive input parameters to the estimate of *Profitability Index* are the value of newsprint (*IRNEWS*), the energy consumed during refining (*SEC*) and pulp mill and newsprint recoveries - Table (7.8). Due to the driving influence of the newsprint production component on the entire enterprise, it may seem reasonable that these parameters have the largest effect on profitability. In addition, as profit is calculated as the difference of two large sums, incomes and costs, and income is strongly related to the value of products sold, the unit value of newsprint (and hence in turn the amount of newsprint produced) is expected to have leverage on profitability.

Discount rate also rated among the ten most sensitive input parameters, but this was based upon the allowable variation in discount rate of ±20%, a range in discount rate of 4% to 6%. As discussed in Chapter 6, the choice of discount rate is dependent upon factors such as risk. However, Klemperer *et al.* (1994) have suggested that the appropriate discount rate might vary from 3% to 10%. The assumptions used in the current analysis have different degrees of certainty, but all were arbitrarily allowed to vary the same relative amount in the sensitivity analysis. The results of this sensitivity analysis reflect the constraints imposed upon input parameters by this arbitrary variance, but were used simply to indicate the first parameters which needed clarifying in subsequent modeling efforts. Refinement of the model inputs to any further extent is beyond the scope of this work as actual production system inputs are generally considered to be commercially sensitive.

7.4.1 An Objective for the Future

The basis of this work relies on the ability to predict a production system, which will reflect the utilisation of wood 25 years into the future. The approach taken was to predict future utilisation of wood resource on systems we see in place today, a solid starting point. However the world may be a different place by the time (as yet unplanted) trees reach maturity. For example, darker paper with more lignin is likely to be acceptable to the environmentally conscious consumer of the future. Fillers such as agricultural waste may be used or breakthroughs in print technology may relax the need for certain fibre types. Two major potential changes which may have impact on future markets (as discussed by Greaves 1999) for flitch timber and newsprint are: (a) the changing nature of the forest resource; (b) the possibility of a taxation on carbon emissions; and (c) the diminishing returns for newsprint as a continuing trend.

The domestic timber supply within Australia has traditionally been dominated by the availability of slow-grown native forest wood. The future timber and paper industries, however, face reduced native forest logs and may expect more intensely grown plantation resource. This could potentially affect the production enterprise with different product possibilities becoming more or less attractive and an eventual change in consumption patterns.

The introduction of a carbon emissions tax may ideally increase the cost of alternatives to timber and newsprint. The carbon neutrality of forest products, and the potential opportunity cost of leaving the standing plantation as a carbon store may considerably alter the value of forest products (Greaves 1999).

The economic model presented is suffuciently flexible to cope with these possibilities, however constraints may need to be placed on the current model to ensure a breeding program is not proceeding toward a 'dead-end' in these circumstances. It is obviously possible to develop specialised populations for specific breeding objectives but dangerous to direct an entire breeding population down such a dangerous and narrow road.

7.5 Conclusion

The system defined in the current work represents a vertically integrated forestry enterprise which grows radiata pine to produce timber flitches and high brightness newsprint from thermomechancial pulp. Within this enterprise, trees are grown without pruning but with two commercial thinnings, with utilisation of all harvested under-bark volume. The enterprise produces 620 cubic metres of under-bark (merchantable) volume per hectare of which 23.5% is sold as timber flitch, with the remainder pulped to produce approximately 318 (oven dry equivalent) tonnes of newsprint. The newsprint production line accounts for 91% of overall income, but is less profitable than the flitch product line when growing, harvesting and transport costs are apportioned to the business components according to volume consumed (respective profitability indices are 33% and 18.8%).

Chapter 8

An economic breeding objective for plantation radiata pine grown to produce timber flitch and newsprint: (b) Biological traits with an influence on the production system

Chapters 7 and 8 have been combined for publishing as:
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8.1 Introduction

Ponzoni and Newman (1989), following Ponzoni (1986), defined the third and fourth stages in the development of a breeding objective function (see Chapter 6) as:

- the determination of the biological traits influencing income and costs; and
- the derivation of economic weights for each trait, thus allowing the breeding objective function to be formally defined.

Following this method, Chapter 7 has defined the enterprise production system and the current chapter defines the traits for which economic weights must be

estimated and examines their impact on the production system. Economic weights are subsequently estimated for each of these traits and a breeding objective function (i.e. a function defining the genetic worth of each aggregate genotype) was formerly defined.

The concept of an aggregate genotype (H) was first presented by Hazel (1943), providing a structure upon which multiple traits of differing economic worth can be accommodated:

$$H = w_1G_1 + w_2G_2 + ... + w_nG_n \qquad (8.1)$$

where:

- G_1 to G_n are the genetic characteristics (or breeding value) of an individual for traits 1 to n; and
- w_1 to w_n are the respective economic weights for each trait.

The economic weights presented in Equation (8.1) may be defined as the marginal changes in the economics of the production system resulting from changes in one unit of each trait respectively, while all other traits are held constant (Borralho *et al.* 1993). Cotterill and Dean (1990) defined economic weights as:

> *"...the additional profit that may be expected from a one unit increase in trait X (say a 1 cm² increase in sectional area of stem) relative to that from a one unit increase in trait Y (1 kg/ m³ increase in wood density)".*

By definition then, economic weights represent the economic advantage of a unit increase in a given trait, when all other traits are held constant.

Moav (1973) estimated the economic value of genetic improvement for different perspectives concluding that the relative value of trait improvement may change depending upon the perspective. In line with Moav's argument, Greaves (1999) calculated economic weights for a number of different perspectives, including:

- incremental **net present value** of improvement **per hectare**;
- incremental **net present value** of improvement **per unit of product** (both per m^2 of liner-board and per m^3 of sawn timber);
- incremental **net present value** of improvement **per cubic metre of roundwood** produced from the forest;
- internal rate of return; and

- profitability index.

By calculating the genetic correlation between sets of economic weights (the methodology is described by James 1982), Greaves (1999) showed that there was very little difference between economic weights estimated from each perspective. However, Anthony and Reece (1989), in discussing the application of economic indicators to long-term investment decision analysis, conclude that when choosing between investment options, the profitability index is a better indicator than net present value or internal rate of return. Firstly, the net present value of different investment options (or trait improvements in this case) can't be justifiably compared unless the investments are of the same size. Further, if the changes in each trait differentially influence the relative size of the components of the production system, there may be no unit basis which does not invalidate the net present value evaluation preference criteria of equal investment. Secondly, Anthony and Reece (1989) argue that internal rate of return may not always give the correct preference when investment options have differing patterns of investment return. Indeed, from the production enterprise modelled by Greaves (1999), traits such as branch size were suggested to alter the pattern of returns.

8.2 Traits influencing the production system

Which traits should we improve to increase the profitability of flitch grade lumber and the profitability of thermomechanical pulping to produce newsprint? Different end-products vary in their specific requirements and thus in potential breeding objective traits (Raymond – *pers comm*), yet there is much commonality in many requirements (Shelbourne *et al.* 1997). Although different breeding objective traits may be required in the current case for timber flitches and newsprint production, it may well be the case that these can be improved through selection for the same criteria.

Shelbourne *et al.* (1997) discusses the formal development of breeding objectives for radiata pine for end product use, and identifies a large number of traits with potential as breeding objective traits for this application. For example, the profitability of growing a forest plantation is strongly affected by such traits as survival (investigated in Chapters 12 and 13), health, form and growth rate of trees within the plantation. These factors can be represented by such breeding objective traits as recoverable volume per hectare, adaptability, disease resistance and log quality. Due to the fact that establishment costs must be compounded to the end of the rotation, any factors affecting rotation length, especially growth rate,

effectively control profitability of the forest growing phase (Shelbourne *et al.* 1997). However variation in log quality and wood quality affecting product values are likely to have dominant effects on the profitability of processing and marketing end products. Indeed, the improvement of traits affecting, primarily, end product profitability may have far more impact on total profitability than improvement of tree growing traits (Greaves 1999, Shelbourne 1997), particularly for a vertically integrated industry (Goddard 1998).

For a timber flitch product, such breeding objective traits that can be considered are: the maximum recovery of merchantable wood (long internodes, unpruned logs, low bark content), stability (on drying, remanufacture etc), mechanical performance (stiffness, strength, hardness) and possibly appearance (minimum of resin pockets, needle traces, checking, other blemishes, a light colour). This final issue would have some bearing on the price expected from the sale of the flitch product to a saw mill, if the sawmill buyer was to sell appearance grade boards. However, it is assumed here that flitches would be cut into structural timber by the sawmiller and hence appearance issues are irrelevant. The stability of solid wood products amounts to maintaining shape and size during processing, drying, reprocessing, and in use. Similarly, good mechanical performance of wood is needed for stiffness (modulus of elasticity) and strength (modulus of rupture) and often surface hardness.

For a newsprint grade paper produced via thermomechanical pulping, such breeding objective traits that can be considered are: reduced power consumption, increased bleachability, improved paper properties (strength properties, for example tear and tensile strengths, and optical properties, for example opacity). Wood density and tracheid characteristics have shown to be important for reconstituted fibre products in radiata pine (Uprichard *et al.* 1994, Kibblewhite and Shelbourne 1997, Nyakuengama 1997, Chapters 4 and 5).

To date, most of the relationships developed between production system components and traits affecting the economics of the production enterprises are based on unconfirmed relationships and on *a priori* reasoning or educated guesses . Chapters Four and Five present some recent work in this area, relating tracheid length, wood density, tracheid coarseness and wood brightness to thermomechanical pulping and newsprint production costs. Branch size, stem sweep, stem taper and timber stiffness were all reported by Greaves (1999) as affecting the profitability of an objective aimed at producing structural timber and liner-board from unpruned radiata pine. An account of tree growth has long been known to affect the cost of growing a plantation (Borralho *et al.* 1993), while the bark thickness of harvested logs has also been suggested to have an impact on the

costs of harvesting and transport (John Simpson- pers. comm.). Bark fragments have been widely shown to have a negative impact on pulp and paper properties if carried through from the debarking and chipping stages of the process into refining (Smook 1992).

The choice of traits used in the present thesis was the outcome of much deliberation with the key considerations being:

- complete coverage of all aspects of the production system defined in Chapter 7;
- historical perceived performance;
- performance as indicated by previous work in this field (see Chapters 4 and 5); and
- availability of data for construction of necessary relationships.

James (1987) and Woolaston and Jarvis (1995) have argued that decisions regarding which traits to include in the breeding objective be based purely on economic grounds, and not on whether they are difficult or easy to measure or change genetically (see Chapter 6). Subsequently, the availability of genetic parameters or viable selection systems were not used as criteria for inclusion of traits in the current work. Cotterill and Dean (1990) recommend that tree breeders should try to limit the number of traits in the breeding objective. However as discussed by Woolaston and Jarvis (1995), this is unnecessary if sound economic and genetic information is available for all traits affecting income and expense. Indeed, Gjedrem (1972) concluded that all traits of economic importance should be included in the definition of a breeding objective, as excluding a trait is effectively equivalent to assigning that trait an economic weight of zero. Therefore ten traits, selected as having an influence on the costs and incomes of the current production enterprise, were evaluated in the current work:

- mean annual increment (*MAI*)
- bark percentage (*BRK*)
- branch index (*BIX*)
- stem sweep (*SWE*)
- stem taper (*TAP*)
- basic density (*DEN*)

- basic working stress of timber (*BWS*)
- mean tracheid length (*LEN*)
- mean tracheid coarseness (*CRS*)
- mean wood brightness (*BRG*).

The influence of each of these traits on the production system can be separated into primary and secondary effects. Primary effects are considered to be direct changes on a component of the production system model. Secondary effects were assumed to be effects on a production system cost or income component due to changed wood flows. Thus, the secondary effects as considered here relate to per-hectare effects and if the model was defined from a different perspective such as per cubic metre of sawn timber for example, the secondary effect of each trait would be different than that defined here.

8.3 Methods

8.3.1 Modeling the effects of trait change

The following sections define each trait identified in the previous section and describe the effect of that trait on the enterprise production system wood-flows, costs and incomes (the production system was defined in Chapter 7).

8.3.1.1 Mean Annual Increment

Mean annual increment (*MAI*) was defined as the mean annual incremental volume per hectare with units of cubic metres per hectare per year (m^3/ha/yr). Although not constant throughout the life of the plantation, a simplifying assumption, that *MAI* is taken at rotation age, was adopted for the current model. The primary effects of increasing *MAI* were to increase harvestable volume and to increase establishment costs. Harvestable under-bark volume per hectare (*VOLHARV*) was assumed to be directly proportional to *MAI* for a given rotation length at a given harvesting operation *y*, which translates to:

$$VOLHARV_{yNEW} = VOLHARV_{yBASE} \frac{MAI_{NEW}}{MAI_{BASE}} \qquad (8.2)$$

where:

- *BASE*-subscripted values are assumed values prior to change and listed in Tables (7.1) to (7.4) in the previous chapter; and

- *NEW*-subscripted values are the values following trait change.

Rotation length and tree-size were assumed to remain unchanged in relation to changes in *MAI*. Stocking however, was assumed to have been increased in direct proportion with *MAI*, leading to more trees which are the same as those grown at the *BASE*, or unimproved, *MAI*. This follows the method of Greaves (in review). Growing costs were increased to accommodate increased establishment costs (*EST*) associated with increased stocking, assuming that a fraction of the establishment costs were directly related to planting stocking (*ESTSTOCK*), being seedling costs and a component of planting costs. Hence:

$$EST_{NEW} = EST_{BASE}\left[\left(1-\frac{ESTSTOCK}{100}\right)+\left(\frac{ESTSTOCK}{100}\right)\times\left(\frac{MAI_{NEW}}{MAI_{BASE}}\right)\right] \qquad (8.3)$$

Increases in growth rate have been widely used to justify either a reduced rotation length or reduced stocking, however there is a confounding effect of changes in other traits associated with these management options. The simplifying assumption used by Greaves (*in review*) was that increasing *MAI* simply provides more of the same "type" of tree. This assumption will be examined in greater detail later in this chapter.

In addition to the primary affects just discussed, an increase in *MAI* resulted in increases in the production of all wood products (on a per-hectare basis) with associated increases in income, and the increase of all per-hectare harvesting, transport and wood conversion costs. This may be described as a secondary wood-flow effect.

8.3.1.2 Bark Percentage

Bark percentage (*BRK*) was defined as the mean volume of bark per hectare of forest, expressed as a percentage of the total harvested log volume (i.e. bark plus wood). The primary effect of increasing *BRK* was an increase in the bark mass (*BMASS*), and hence an increase in the green volume of logs:

$$HARVWT_{yBASE} = WMASS_{yBASE} + BMASS_{yBASE} \qquad (8.4)$$

then

$$HARVWT_{yNEW} = HARVWT_{yBASE} + \left(BMASS_{yNEW} - BMASS_{yBASE}\right) \qquad (8.5)$$

where:

- $HARVWT_y$ is the per-hectare harvested mass of wood and bark, by harvesting operation y, in green tonnes;
- $WMASS_y$ is the total mass of green wood, in tonnes, assumed to be independent of increases in *BRK*; and:

$$BMASS_{yNEW} = \frac{VOLHARV_y \times \left(\frac{BRK_{yNEW}}{100}\right)}{\left(1 - \frac{BRK_{yNEW}}{100}\right) \times BGD} \quad (8.6)$$

where:

- *BGD* is the green density of bark, assumed to be constant (Chapter 7, Equation 7.12)

As the costs of harvesting and transporting harvested logs to the mill site are expressed per green tonne of log in the current model, increasing *BRK* led to an increase in both of these costs. Also, due to a greater overall log mass arriving at the mill site, the debarking costs (expressed per cubic metre of delivered log) increased as *BRK* increased. However this change in overall log mass did not flow through the production process (as opposed to the way *MAI* was modelled), as the total harvested under-bark volume (i.e. wood volume) was assumed to remain constant. Only the total harvested and delivered volume (*TODELVOLy*) was affected. In addition it was also assumed that the stringent chip screening process prior to refining prevented any significant degree of bark carrying through into the TMP and affecting the processing costs.

8.3.1.3 Branch Index

Branch Index (*BIX*) was defined as the average of the diameters of the largest branch in each of the four quadrants of a stem or log (Cown 1992), expressed in centimetres. *BIX* is an indicator of tree branch size and there are many methods for assessing this trait (Cown 1992). However, in this chapter, the New Zealand method of estimating *BIX* was adopted due to the availability of relationships with sawn-timber value (see Greaves 1999). The primary effect of increasing branch size was to decrease the value of sawn (*IRSAWNFL*) or chipped (*IRCHIPFL*) timber flitch produced by reducing the final structural timber grade. Thus:

$$IRSAWNFL_{NEW} = IRSAWNFL_{BASE} + (BIX_{NEW} - BIX_{BASE}) \times BIXSAWNFL \quad (8.7)$$

where:

- *BIXSAWNFL* is the change in the average value of rough green sawn flitch per cubic metre associated with an increase in *BIX* of one centimetre (assumed to be -\$19/m^3 per cm); and

$$IRCHIPFL_{NEW} = IRCHIPFL_{BASE} + (BIX_{NEW} - BIX_{BASE}) \times BIXCHIPFL \qquad (8.8)$$

where:

- *BIXCHIPFL* is the change in the average value of rough green chipped flitch per cubic metre associated with an increase in *BIX* of one centimetre (assumed to be -\$19/m^3 per cm).

The assumed values of *BIXSAWNFL* and *BIXCHIPFL* were derived from predictions of grade out-turn as a function of *BIX* made using the SAWMOD computer simulation package (Whiteside and McGregor 1986), for assumed log sizes and an assumed grade price structure.

A simplifying assumption employed in the current chapter was to assume that increasing branch size does not change flitch recovery in sawing. Larger branches may encourage a sawmiller to change their cutting pattern to avoid branches, producing less timber but timber of higher quality, thus reducing the impact on the total value of recovered timber. However, as discussed by Greaves (1999) the change in branch size with breeding will be small and the simplifying assumption was considered by that author to be acceptable. In addition, the current model (Chapter 7) requires that a percentage of timber flitches is also produced from a chipper canter method, where less practical control can be exerted on the quality of the final flitch product, irrespective of prior log grading and equipment optimisation.

8.3.1.4 Stem Sweep

Stem sweep (*SWE*) was defined as the maximum log deviation over a length of log in units of millimetres per metre (mm/m). The primary effect of increasing stem sweep was a reduction in overall flitch recovery, the percentage volume of flitch cut per unit volume of roundwood sawn (*SAWNREC*) following:

$$SAWNREC_{yNEW} = SAWNREC_{yBASE} + (SWE_{NEW} - SWE_{BASE}) \times SWESAWNREC \qquad (8.9)$$

where:

- *SWESAWNREC* is the change in the average recovery of sawn flitch associated with an increase in *SWE* of one millimetre per metre (assumed to be –0.5% per mm/m); and

$$CHIPFLREC_{yNEW} = CHIPFLREC_{yBASE} + (SWE_{NEW} - SWE_{BASE}) \times SWECHIPREC \qquad (8.10)$$

where:

- *SWECHIPREC* is the change in the average recovery of flitch produced from the chipper canter, associated with an increase in *SWE* of one millimetre per metre (assumed to be –0.5% per mm/m).

The assumed values of *SWESAWNREC* and *SWECHIPREC* were estimated from volume recovery predictions made using the SAWMOD computer simulation package (Whiteside and McGregor 1986) for assumed log sizes.

The fraction of sawn waste was assumed unchanged by an increase in *SWE* and hence an increase in *SWE* resulted in $VOLCHIP_y$ being increased (i.e. the volume of harvested wood being directed to the chipper canter). Likewise, the fraction of chip waste was assumed to be unchanged by an increase in *SWE* and hence an increase in *SWE* resulted in $VOLTMPCHIP_y$ being increased (i.e. the volume of pulpwood chips produced from the chipper canter for thermomechanical pulping. The sawing costs remain unchanged as sawing cost is assumed to be directly related to the volume of sawn log. The chipping costs remain the same, as the same volume of wood is being chipped, however a lower volume of flitch is recovered from the chipper canter.

The secondary effects of increasing *SWE* were to: (i) reduce income from the sale of sawn flitches; (ii) reduce income from the sale of chipped flitches; and (iii) increase the per-hectare costs of pulping and newsprint manufacture and the per-hectare income from sale of newsprint produced, in line with the increased chip volume ($VOLCHIP_y$).

8.3.1.5 Stem Taper

Stem taper (*TAP*) is defined in the current chapter as the change in log diameter per metre of log length, with the units of millimetres per metre (mm/m). The primary effect of increasing *TAP* was a reduction in sawn flitch and chipper-canter flitch recovery, following:

$$SAWNREC_{yNEW} = SAWNREC_{yBASE} + (TAP_{NEW} - TAP_{BASE}) \times TAPSAWNREC \quad (8.11)$$

where:

- *TAPSAWNREC* is the change in the average recovery of sawn flitch associated with an increase in *TAP* of one millimetre per metre (assumed to be –0.1% per mm/m); and

$$CHIPFLREC_{yNEW} = CHIPFLREC_{yBASE} + (TAP_{NEW} - TAP_{BASE}) \times TAPCHIPREC \quad (8.12)$$

where:

- *TAPCHIPREC* is the change in the average recovery of flitch produced from the chipper-canter, associated with an increase in *TAP* of one millimetre per metre (assumed to be –0.1% per mm/m).

The assumed values of *TAPSAWNREC* and *TAPCHIPREC* were estimated from volume recovery predictions made using the SAWMOD computer simulation package (Whiteside and McGregor 1986) for assumed log sizes.

The secondary effects of *TAP* due to changes in wood-flows within the defined production system are equivalent to those reported for stem sweep above. Increases in *TAP* result in an indirect decrease in the income derived from the sale of sawn flitch and flitch produced from the chipper canter. Increased *TAP* also leads to increases in the per-hectare costs of transport, pulping and newsprint manufacture, and an increase in the per-hectare income from sale of newsprint.

8.3.1.6 Basic Density

Basic density (*DEN*) is defined as the assumed oven dry (OD) stand average mass of wood per green cubic metre, expressed in units of kilograms per cubic metre (kg/m^3).

The primary effects of basic density on the production enterprise were based on those relationships derived in Chapters 4 and 5. The basic density of pulpwood following a change in stand basic density ($PWDEN_{NEW}$) by harvesting operation y was estimated from the assumed stand average basic density following:

$$PWDEN_{NEWy} = PWDEN_{BASEy} + \left(DEN_{NEWy} - DEN_{BASEy}\right) \quad (8.13)$$

where:

- DEN_y is the mean basic density of the stand (kg/m^3) at harvesting operation y; and

- $PWDEN_y$ is the mean basic density of pulp wood (i.e. wood chips entering the TMP process, by harvesting operation y.

Now, pulpwood density is related to the energy required to refine a tonne of wood-chips into thermomechanical pulp (TMP), following Chapter 4:

$$SEC_{BASEy} = 3748 - (1.29 \times LEN_{BASE} \times PWDEN_{BASEy}) \quad (8.14)$$

where:

- SEC_y is the specific energy consumed when converting wood chips into TMP, by harvesting operation y, expressed in kilowatt hours per tonne (kWhr/t); and

- LEN_{BASE} is the "base" assumed mean tracheid length, expressed in millimetres.

The specific energy consumption resulting from an increase in pulpwood density (SEC_{NEWy}) by harvesting operation y, can therefore be estimated from:

$$SEC_{NEWy} = 3748 - (1.29 \times LEN_{BASE} \times PWDEN_{NEWy}) \quad (8.15)$$

Increases in mean stand basic density (DEN_{NEW}) can thus be seen to decrease the energy consumed to refine an OD tonne of pulpwood chips. From Chapter 7, this in turn, leads to a decrease in the cost of producing an OD tonne of TMP (*TMPRATE*).

Basic density also has a direct effect on the strength properties of the final newsprint sheet according to the relationships developed in Chapter 4 between pulp handsheet tear and tensile strength and estimates of pulpwood chip basic density. This assumes that estimates of pulp handsheet strength parameters provide a reasonable predictor of newsprint strength (see Chapter 4). Pulpwood density has been shown to effect the tear strength of a pulp handsheet (*TE*) according to:

$$TE_{BASEy} = -1.8 + (1.33 \times LEN_{BASE}) + (0.0145 \times PWDEN_{BASEy}) \quad (8.16)$$

and to affect the tensile properties of a pulp handsheet (*TN*) according to:

$$TN_{BASEy} = 36.1 + (2.04 \times LEN_{BASE}) - (0.013 \times PWDEN_{BASEy}) \quad (8.17)$$

Therefore, the estimates of *TE* and *TN* following a change in basic density can be estimated from:

$$TE_{NEWy} = -1.8 + (1.33 \times LEN_{BASE}) + (0.0145 \times PWDEN_{NEWy}) \quad (8.18)$$

and

$$TN_{NEWy} = 36.1 + (2.04 \times LEN_{BASE}) - (0.013 \times PWDEN_{NEWy}) \quad (8.19)$$

Increases in basic density were thus shown to result in an increased newsprint tear strength, but a decreased newsprint tensile strength. From Equation 7.41 (Chapter 7) therefore, an increase in basic density determines that less kraft pulp needs to be added to the pulp furnish to improve the final newsprint tear strength to a minimum standard. However Equation (7.41) also indicates that an increase in *DEN* demands that more kraft be added to the furnish to improve the final newsprint tensile strength to a minimum standard. The combined result of these conflicting effects is a small decrease in the amount of kraft pulp added to the final pulp furnish and hence a decrease in kraft pulp costs (*CKRA*). However, as less kraft pulp is added, the mass of the pulp furnish is reduced and subsequently the cost of converting the pulp furnish to newsprint and the income derived from the sale of newsprint is reduced. This is a secondary effect as the reduced costs and returns are due to a change in wood-flows. Other secondary effects of *DEN* were a small increase in the green density of logs and chips leading to small increases in harvesting and transport costs, and an increase in the OD mass of pulp produced from a given wood-chip volume. This last effect leads to increases in per-hectare costs of pulping and newsprint production and income from the sale of newsprint.

As discussed by Greaves (1999), although there is evidence that increasing basic density increases the value of sawn timber (SAWMOD, NZ-FRI 1997), these gains were assumed in the present chapter to be derived fundamentally from an increase in Basic Working Stress (which shows a strong relationship with wood density in radiata pine, e.g. Matheson 1997). Hence no direct increase in sawn or chipped flitch value with increasing density was assumed.

8.3.1.7 Basic Working Stress

Structural timber is sold by F-grade which relates to the Basic Working Stress (*BWS*) of the timber (Standards of Australia AS1748-1978). For example, the F4-grade has a *BWS* of between 4.3 and 5.5 megapascals. The primary effect of

increasing *BWS* was an increase in the average value of sawn (*IRSAWNFL*) and chipped (*IRCHIPFL*) flitch by increasing the final grade of structural timber flitches:

$$IRSAWNFL_{NEW} = IRSAWNFL_{BASE} + (BWS_{NEW} - BWS_{BASE}) \times BWSSAWN \quad (8.20)$$

where:

- *BWSSAWN* is the change in the average value of rough green sawn flitch per cubic metre associated with an increase in *BWS* of one megapascal (assumed to be \$16/m^3 per MPa); and:

$$IRCHIPFL_{NEW} = IRCHIPFL_{BASE} + (BWS_{NEW} - BWS_{BASE}) \times BWSCHIP \quad (8.21)$$

where:

- *BWSCHIP* is the change in the average value of rough green chipped flitch per cubic metre associated with an increase in *BWS* of one megapascal (assumed to be \$16/m^3 per MPa).

The assumed values of *BWSSAWN* and *BWSCHIP* were estimated according to the method of Greaves (1999), whereby a normal distribution for *BWS* was fitted to SAWMOD-predicted grade out-turns and then deriving the change in average product value associated with a shift in the distribution across an assumed timber grade price structure (see Greaves 1999).

Wood-flows were unchanged by increased *BWS*, and the only change in the production system was the increase in income derived from the sale of sawn-timber.

8.3.1.8 Tracheid Length

Tracheid length (*LEN*) is defined as the mean length of plantation wood tracheids, expressed in millimetres. The primary effects of *LEN* on the production enterprise are similar to those described for wood density previously. Increases in tracheid length decrease the specific energy consumed during refining according to:

$$SEC_{NEWy} = 3748 - (1.29 \times LEN_{NEW} \times PWDEN_{BASEy}) \quad (8.22)$$

This leads to an decrease in the cost of producing an OD tonne of TMP (*TMPRATE*)- see Chapter 7.

Tracheid length also has a direct effect on the strength properties of the final newsprint sheet according to the relationships developed in Chapters 4 and 5.

Increases in tracheid length result in an increased newsprint tear strength and an increased tensile strength according to:

$$TE_{NEWy} = -1.8 + (1.33 \times LEN_{NEW}) + (0.0145 \times PWDEN_{BASEy}) \quad (8.23)$$

and

$$TN_{NEWy} = 36.1 + (2.04 \times LEN_{NEW}) - (0.013 \times PWDEN_{BASEy}) \quad (8.24)$$

where:

- TE_{NEW} is the tear strength, expressed in mNm^2/g, by harvesting operation y, following a change in tracheid length; and
- TN_{NEW} is the tensile strength, expressed in Nm/g, by harvesting operation y, following a change in tracheid length.

This determines that less kraft pulp be added to the pulp furnish to improve the final newsprint tear and tensile strengths to a minimum standard. Ultimately, this results in a decrease in the amount of kraft pulp added to the final pulp furnish and hence a decrease in newsprint costs.

The secondary effects of *LEN* were such that as less kraft pulp is added, the mass of the pulp furnish is reduced and subsequently the cost of newsprint production and the income derived from the sale of newsprint is reduced.

8.3.1.9 Tracheid Coarseness

Tracheid coarseness (*CRS*) is defined as the mean coarseness of plantation wood tracheids, expressed in milligrams per metre of tracheid (mg/m). Tracheid coarseness influences the opacity of a newsprint sheet (See Chapters 4 and 5) according to:

$$OP_{BASE} = 88.27 - (10.71 \times CRS_{BASE}) \quad (8.25)$$

where:

- OP_{BASE} is the "base" assumed opacity of a newsprint sheet, expressed as a percentage; and
- *CRS* is the mean tracheid coarseness, expressed in mg/m.

The primary effect of an increase in tracheid coarseness is, therefore, to decrease the opacity of the final newsprint sheet following:

$$OP_{NEW} = 88.27 - (10.71 \times CRS_{NEW}) \quad (8.26)$$

where:

- OP_{NEW} is the newsprint sheet opacity following a change in tracheid coarseness.

As opacity decreases from the required sale standard, more filler must be added to the forming newsprint sheet on the paper machine according to Equation (7.43) in Chapter 7. Hence, the cost of filler addition (*CFIL*) increases with increasing tracheid coarseness.

However, a secondary effect of increasing *CRS* is that as more filler is added to the forming newsprint sheet, the mass of newsprint increases. This increase of newsprint mass on a per hectare basis, increases the cost of converting the pulp furnish mass to newsprint mass (on a per-hectare basis) and the income per hectare from the sale of newsprint.

8.3.1.10 Wood Brightness

Wood brightness is defined as the mean percentage reflectance of light by wood at 457nm (situated within the visible blue region of the colour spectrum). From the relationships developed in Chapters 4 and 5, wood brightness was shown to be related to the brightness of a newsprint sheet according to:

$$PB_{BASE} = 33.92 - (0.52 \times BRG_{BASE}) \quad (8.27)$$

where:

- PB_{BASE} is the "base" assumed ISO brightness of a newsprint sheet; and
- *BRG* is the wood brightness, expressed in percentage terms.

Therefore, newsprint brightness following a trait change (PB_{NEW}) can be estimated from:

$$PB_{NEW} = 33.92 - (0.52 \times BRG_{NEW}) \quad (8.28)$$

Increasing *PB* results in decreasing the amount of bleach required to achieve a specified newsprint sheet brightness and hence a reduction in bleaching costs. There were no secondary effects of wood brightness

8.3.2 Calculating Economic Weights

The economic value of genetic improvement in the current work was estimated from two different economic perspectives:

- incremental net present value of improvement per hectare; and
- profitability index.

The economic weight for each trait calculated under the net present value per hectare method (W_{NPV}) was determined after:

$$W_{NPV} = P_{PV\_NEW} - P_{PV\_BASE} \quad (8.29)$$

where:

- P_{PV_BASE} is the net present value of the production system prior to a trait-change; and
- P_{PV_NEW} is the net present value of the production system following a trait-change.

The economic weight for each trait calculated under the profitability index method (W_{PI}) was derived from the change in profitability index associated per unit increase in that trait:

$$W_{PI} = PI_{NEW} - PI_{BASE} \quad (8.30)$$

where:

- W_{PI} is the economic weight, representing the incremental return on investment associated with a unit increase in any given trait (in dollars per dollar spent);
- PI_{BASE} is the profitability index of the enterprise prior to a trait change; and
- PI_{NEW} is the profitability index of the enterprise following a trait change.

Estimates of Net Present Value and Profitability Index were calculated according to the methods described in Chapter 7.

By definition, economic weights represent the economic advantage of a unit increase in a given trait, when all other traits are held constant and thus do not provide an indication of the relative importance of each trait with respect to each other. For example, the economic weight of MAI represents the economic

advantage of an increase in MAI by one m^3/ha/yr from 20 to 21 m^3/ha/yr – an increase of 5%, while the economic weight for tracheid length represents the economic advantage of an increase in tracheid length of 1 mm from 2.5 to 3.5 mm – an increase of almost 30%. In addition, the economic weight in some instances, for example tracheid coarseness represents the economic advantage of an increase of 1 mg/m from 0.5 to 1.5 mg/m – an increase of 200% but, more importantly a value well outside the realistic phenotypic range of this trait. Hence the economic weights as derived offer little indication of the value of improvement in each trait. In order to better understand the value of improvement in each trait, either genetic or silvicultural, the value of a 10% increase in each trait was investigated following Equations (8.30) and (8.31) for the Net Present Value and Profitability Index perspectives respectively:

$$W_{(10\%)NPV} = P_{PV(10\%)NEW} - P_{PV(10\%)BASE} \quad (8.31)$$

where:

- $W_{(10\%)NPV}$ is the economic coefficient associated with a 10% increase in each trait;
- $P_{PV(10\%)NEW}$ is the net present value of profit following a 10% trait increase; and

$$W_{(10\%)PI} = PI_{(10\%)NEW} - PI_{BASE} \quad (8.32)$$

where:

- $W_{(10\%)PI}$ is the economic coefficient associated with a 10% increase in each trait; and
- $PI_{(10\%)NEW}$ is the profitability index following a 10% trait increase.

8.3.3 Simulation of the model and Sensitivity Analysis

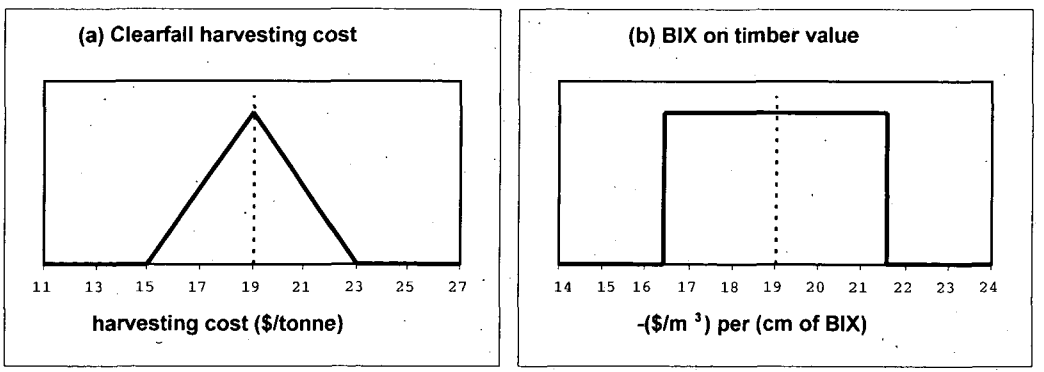
A simulation model of the influence of trait change on the production system detailed in Chapter 7 was constructed using Excel 97 spreadsheet software (Microsoft 1997). The mean starting values for each trait are shown in Table 8.1. These values were based on advice given by John Simpson (pers. comm.) and may be considered appropriate as a general description of the local forest industry in South-eastern Australia.

Table 8.1- Assumed production system parameters: assumed unimproved stand-average trait means.

Parameter	Description	Units	Value
MAI	Mean annual increment	m^3/ha/yr	20
BRK	Bark percentage of total delivered volume	%	8
BIX	Branch index	cm	5
SWE	Stem sweep	mm/m	3
TAP	Stem taper	mm/m	5
DEN	basic density of the stand averaged across all harvesting operations	kg/m^3	400
BWS	Timber basic working stress	MPa	6.5
LEN	Mean tracheid length	mm	2.5
CRS	Mean tracheid coarseness	mg/m	0.5
BRG	Mean wood brightness	%	50

Spearman's Rank Order Correlation was utilised to determine the trait change input parameters having the greatest influence on the estimated base profitability index and the change in profitability index associated with trait change. Monte Carlo simulation was used to generate 10,000 trait change input parameter sets, and for each parameter set economic weights were estimated. All production system inputs were allowed to vary by ±20% with an assumed triangular distribution and all trait change inputs by ±20% with an assumed uniform distribution: examples are given in Figure 8.1

Figure 8.1- Graphical depiction of the probability distributions assumed for the Monte-Carlo simulation analysis to gauge the sensitivities of the various input parameters: (a) Triangular distribution for clearfall harvesting cost; and (b) Uniform distribution for the effect of branch size (*BIX*) on the value of timber flitch. Dashed lines represent assumed "base" values.



8.4 Results and Discussion

8.4.1 The effects of trait change on the Production System

The hypothetical production enterprise upon which this chapter was based (as detailed in Chapter 7) is assumed to grow, harvest, transport, chip or saw timber flitches, and process wood chips via thermomechanical pulping to high brightness newsprint. The following section presents the impact that individual trait changes have on the production system wood flows, costs, and incomes (returns). The effect of a 10% increase in each trait individually is examined from the perspective of the costs and incomes per hectare. The mechanisms by which trait change influences the production system profitability, as described in the Methods section, are presented.

8.4.1.1 Mean Annual Increment

Increasing *MAI* by 10%, which corresponds to an increase of 2 cubic metres per hectare per year, increases the under-bark volume yield of the forest at each harvesting operation ($VOLHARV_y$) by 10%. This increase in volume has an effect on the entire production system as all wood flow values are increased by 10% (Table 8.2). Assuming that rotation length and individual tree size remains unchanged (see Methods, Section 8.3.1.1), an increase in *MAI* of 10%, increases the growing costs directly by $217 per hectare (Table 8.3).

The increased volume of flitches and the increased mass of newsprint produced (Table 8.2) resulting from increased wood flow due to an increase in *MAI*, lead to increased returns from the sale of these products. However the costs associated with producing them also rise due to the same increased wood flow. Table 8.3 shows that, overall, a 10% increase in MAI increases the overall enterprise *Net Present Value* (P_{PV}) by $8,418 and increases the *Profitability Index* (*PI*) by 0.64% (Table 8.3).

Table 8.2- The effect of a 10% trait increase on enterprise wood flows, where "base" values refer to the wood flows before an increase in MAI, "new" values are inclusive of a 10% increase in MAI, and the effected values are highlighted in red.

wood flow (per hectare)		T1 (15 years)		T2 (20 years)		CF (25 years)		Total		unit
		base	new	base	new	base	new	base	new	
delivered volume (incl. bark)	*VOLTOTDEL*	108.7	119.6	130.4	143.5	434.8	478.3	673.9	741.3	m3/ha
bark volume	*VOLBARK*	8.7	9.6	10.4	11.5	34.8	38.3	53.9	59.3	m3/ha
havested volume (under bark)	*VOLHARV*	100.0	110.0	120.0	132.0	400.0	440.0	620.0	682.0	m3/ha
chipped flitch volume	*VOLCHIPFL*	0.0		18.0	19.8	48.0	52.8	66.0	72.6	m3/ha
sawn flitch volume	*VOLSAWNFL*	n/a	n/a	n/a	n/a	80.0	88.0	80.0	88.0	m3/ha
pulp chip volume	*VOLTMPCHIP*	100.0	110.0	98.9	108.8	263.8	290.2	462.8	509.1	m3/ha
thermo-mechanical pulp mass	*MASSTMP*	34.2	37.6	39.2	43.1	114.0	125.4	187.4	206.1	ODt/ha
newsprint furnish	mass sum of	65.8	72.3	74.1	81.5	212.9	234.2	352.8	388.1	ODt/ha
newsprint	*MASSNEWS*	59.2	65.1	66.7	73.3	191.7	210.8	317.5	349.2	ODt/ha
newsprint (area)	*AREANEWS*	1.32	1.45	1.48	1.63	4.26	4.68	7.06	7.76	m^2 ($x10^6$)
thermo-mechanical pulp	*MASSTMP*	34.2	37.6	39.2	43.1	114.0	125.4	187.4	206.1	ODt/ha
cold caustic soak pulp	*MASSCCS*	14.3	15.7	16.3	18.0	47.5	52.2	78.1	85.9	ODt/ha
recycled fibre pulp	*MASSRCF*	8.6	9.4	9.8	10.8	28.5	31.3	46.8	51.5	ODt/ha
chemical kraft pulp	*MASSKRA*	5.2	5.8	4.8	5.3	11.6	12.7	21.6	23.7	ODt/ha
clay filler	*MASSFIL*	3.5	3.9	4.0	4.4	11.4	12.6	18.9	20.8	t/ha

Table 8.3- The effect of a 10% trait increase on costs and returns, where "base" values refer to the cost/return before an increase in MAI, "new" values are inclusive of a 10% increase in MAI, and the effected values are highlighted in red.

cost/return item	Total (P_{PV}/ha) base	new	change
growing cost	$16,873	$17,089	$217
harvesting cost	$12,368	$13,605	$1,237
transport cost	$7,943	$8,737	$794
debarking cost	$7,783	$8,561	$778
chipper/canter cost	$44,523	$48,975	$4,452
sawing cost	$4,400		
pulping cost	$50,774	$55,851	$5,077
bleaching cost	$52,345	$57,580	$5,235
newsprint cost	$129,939	$142,932	$12,994
total costs	**$326,948**	$357,732	$30,784
flitch value	$33,804	$37,184	$3,380
newsprint value	$358,214	$394,035	$35,821
total returns	**$392,018**	$431,219	$39,202
returns minus costs (P_{PV})	**$65,070**	$73,487	$8,418
profitability index (PI)	**19.90%**	20.54%	0.64%

8.4.1.2 Bark Percentage

Increasing *BRK* by 10%, which corresponds to an increase of 0.8% (or, in other words, an increase in 0.95 m^3/ha of bark per 100 m^3/ha of wood), results in a 11% increase in bark volume ($VOLBARK_y$). Hence the total volume of logs harvested and delivered ($VOLTOTDEL_y$) is also increased by an amount equivalent to $VOLBARK_y$ (Table 8.4). The increase in $VOLTOTDEL_y$ is not 10% as the current model assumes that the harvested under-bark volume ($VOLHARV_y$) remains constant. This also determines that no other wood flow values are changed from an increase in bark percentage (Table 8.4).

The increased total delivered volume shown in Table (8.4) results in an increased harvesting cost of $74 per hectare, an increased transport cost of $48 per hectare, and an increased cost of debarking at the mill site of $68 per hectare (Table 8.5). Due to the fact that there are no secondary wood flow effects for the model specified, a 10% increase in *BRK* results in a decrease in *Net Present Value* of $190 (the sum of these costs just outlined), and hence a decrease also in the *Profitability Index* of 0.07% (Table 8.5). It must be noted here, that many mills use bark fired biolers and thus an increase in bark content may reduce the fueling costs. However this consideration was not taken into account with the current model.

Table 8.4- The effect of a 10% trait increase on enterprise wood flows, where "base" values refer to the wood flows before an increase in BRK, "new" values are inclusive of a 10% increase in BRK, and the effected values are highlighted in red.

wood flow (per hectare)		T1 (15 years)		T2 (20 years)		CF (25 years)		Total		unit
		base	new	base	new	base	new	base	new	
delivered volume (incl. bark)	*VOLTOTDEL*	108.7	109.6	130.4	131.6	434.8	438.6	673.9	679.8	m3/ha
bark volume	*VOLBARK*	8.7	9.6	10.4	11.6	34.8	38.6	53.9	59.8	m3/ha
havested volume (under bark)	*VOLHARV*	100.0		120.0		400.0		620.0		m3/ha
chipped flitch volume	*VOLCHIPFL*	0.0		18.0		48.0		66.0		m3/ha
sawn flitch volume	*VOLSAWNFL*	n/a	n/a	n/a	n/a	80.0		80.0		m3/ha
pulp chip volume	*VOLTMPCHIP*	100.0		98.9		263.8		462.8		m3/ha
thermo-mechanical pulp mass	*MASSTMP*	34.2		39.2		114.0		187.4		ODt/ha
newsprint furnish	mass sum of	65.8		74.1		212.9		352.8		ODt/ha
newsprint	*MASSNEWS*	59.2		66.7		191.7		317.5		ODt/ha
newsprint (area)	*AREANEWS*	1.32		1.48		4.26		7.06		m^2 ($\times 10^6$)
thermo-mechanical pulp	*MASSTMP*	34.2		39.2		114.0		187.4		ODt/ha
cold caustic soak pulp	*MASSCCS*	14.3		16.3		47.5		78.1		ODt/ha
recycled fibre pulp	*MASSRCF*	8.6		9.8		28.5		46.8		ODt/ha
chemical kraft pulp	*MASSKRA*	5.2		4.8		11.6		21.6		ODt/ha
clay filler	*MASSFIL*	3.5		4.0		11.4		18.9		t/ha

Table 8.5- The effect of a 10% trait increase on costs and returns, where "base" values refer to the cost/return before an increase in BRK, "new" values are inclusive of a 10% increase in BRK, and the effected values are highlighted in red.

cost/return item	Total (P_{PV}/ha) base	new	change
growing cost	$16,873		
harvesting cost	$12,368	$12,442	$74
transport cost	$7,943	$7,991	$48
debarking cost	$7,783	$7,851	$68
chipper/canter cost	$44,523		
sawing cost	$4,400		
pulping cost	$50,774		
bleaching cost	$52,345		
newsprint cost	$129,939		
total costs	**$326,948**	**$327,138**	**$190**
flitch value	$33,804		
newsprint value	$358,214		
total returns	**$392,018**		
returns minus costs (P_{PV})	**$65,070**	**$64,879**	**-$190**
profitability index (*PI*)	**19.90%**	**19.83%**	**-0.07%**

8.4.1.3 Branch Index

An increase in branch index of 10%, which corresponds to an increase of 0.5cm, decreases the value of timber flitches produced by reducing the final grade of sawn structural timber (see Methods, Section 7.4.1.3). *BIX* does not alter the volume or mass of wood present within the system at any time and as such has no effect on wood flows. As such, a table of the effect of *BIX* on wood-flows has not been presented.

The direct impact of *BIX* on the flitch value is shown in Table (8.6). Overall, a 10% increase in *BIX* decreases the flitch value, and hence the total returns by $1,396, resulting in a *Profitability Index* of –0.43%.

Table 8.6- The effect of a 10% trait increase on costs and returns, where "base" values refer to the cost/return before an increase in BIX, "new" values are inclusive of a 10% increase in BIX, and the effected values are highlighted in red.

cost/return item	Total (P_{PV}/ha) base	new	change
growing cost	$16,873		
harvesting cost	$12,368		
transport cost	$7,943		
debarking cost	$7,783		
chipper/canter cost	$44,523		
sawing cost	$4,400		
pulping cost	$50,774		
bleaching cost	$52,345		
newsprint cost	$129,939		
total costs	**$326,948**		
flitch value	$33,804	$32,408	-$1,396
newsprint value	$358,214		
total returns	**$392,018**	**$390,621**	**-$1,396**
returns minus costs (P_{PV})	**$65,070**	**$63,674**	**-$1,396**
profitability index (PI)	**19.90%**	**19.48%**	**-0.43%**

8.4.1.4 Stem Sweep

A 10% increase in stem sweep (i.e. from 3.0 to 3.3 mm/m) reduces the recovery of flitch by –0.5% as detailed previously (Section 8.3.1.4). Thus the volume of flitch produced either by sawing ($VOLSAWNFL_y$) or by the chipper canter ($VOLCHIPFL_y$) is reduced (Table 8.7). As the waste volume fraction from both sawing and chipping is assumed to remain constant, the volume of pulp chips ($VOLTMPCHIPS_y$) is increased (Table 8.7).

Sawing and chipping cost remain unchanged (see Methods section), however due to the reduced recovery of flitch and the increased volume of wood chips being pulped, the costs of pulping, bleaching and newsprint production were increased as *SWE* increased by 10% (Table 8.8). A 10% increase in *SWE* decreases the *Net Present Value* of the production enterprise by $25 (per hectare), resulting in a *Profitability Index* of –0.04%.

Table 8.7- The effect of a 10% trait increase on enterprise wood flows, where "base" values refer to the wood flows before an increase in SWE, "new" values are inclusive of a 10% increase in SWE, and the effected values are highlighted in red.

wood flow (per hectare)		T1 (15 years) base	T1 (15 years) new	T2 (20 years) base	T2 (20 years) new	CF (25 years) base	CF (25 years) new	Total base	Total new	unit
delivered volume (incl. bark)	VOLTOTDEL	108.7		130.4		434.8		673.9		m3/ha
bark volume	VOLBARK	8.7		10.4		34.8		53.9		m3/ha
havested volume (under bark)	VOLHARV	100.0		120.0		400.0		620.0		m3/ha
chipped flitch volume	VOLCHIPFL	0.0		18.0	17.8	48.0	47.6	66.0	65.4	m3/ha
sawn flitch volume	VOLSAWNFL	n/a	n/a	n/a	n/a	80.0	79.4	80.0	79.4	m3/ha
pulp chip volume	VOLTMPCHIP	100.0		98.9	99.1	263.8	264.8	462.8	463.9	m3/ha
thermo-mechanical pulp mass	MASSTMP	34.2		39.2	39.2	114.0	114.4	187.4	187.8	ODt/ha
newsprint furnish	mass sum of	65.8		74.1	74.2	212.9	213.7	352.8	353.7	ODt/ha
newsprint	MASSNEWS	59.2		66.7	66.8	191.7	192.4	317.5	318.3	ODt/ha
newsprint (area)	AREANEWS	1.32		1.48	1.48	4.26	4.27	7.06	7.07	m^2 ($x10^6$)
thermo-mechanical pulp	MASSTMP	34.2		39.2	39.2	114.0	114.4	187.4	187.8	ODt/ha
cold caustic soak pulp	MASSCCS	14.3		16.3	16.4	47.5	47.7	78.1	78.3	ODt/ha
recycled fibre pulp	MASSRCF	8.6		9.8	9.8	28.5	28.6	46.8	47.0	ODt/ha
chemical kraft pulp	MASSKRA	5.2		4.8	4.8	11.6	11.6	21.6	21.6	ODt/ha
clay filler	MASSFIL	3.5		4.0	4.0	11.4	11.5	18.9	19.0	t/ha

Table 8.8- The effect of a 10% trait increase on costs and returns, where "base" values refer to the cost/return before an increase in SWE, "new" values are inclusive of a 10% increase in SWE, and the effected values are highlighted in red.

cost/return item	Total (P_{PV}/ha) base	Total (P_{PV}/ha) new	change
growing cost	$16,873		
harvesting cost	$12,368		
transport cost	$7,943		
debarking cost	$7,783		
chipper/canter cost	$44,523	$44,565	$42
sawing cost	$4,400		
pulping cost	$50,774	$50,886	$112
bleaching cost	$52,345	$52,465	$120
newsprint cost	$129,939	$130,230	$291
total costs	**$326,948**	$327,513	$565
flitch value	$33,804	$33,530	-$274
newsprint value	$358,214	$359,028	$814
total returns	**$392,018**	$392,558	$541
returns minus costs (P_{PV})	**$65,070**	$65,045	-$25
profitability index (PI)	**19.90%**	19.86%	-0.04%

8.4.1.5 Stem Taper

An increase in stem taper of 10% (i.e. increasing stem taper from 5.0 to 5.5 mm/m) reduces the recovery of flitch by –0.1% as detailed previously (see Methods section). The response of the system to a 10% increase in *TAP* was analogous to the case for stem sweep detailed above. The volume of flitch produced either by sawing ($VOLSAWNFL_y$) or by the chipper canter ($VOLCHIPFL_y$) is reduced (Table 8.9). As the waste volume fraction from both sawing and chipping is assumed to remain constant, the volume of pulp chips ($VOLTMPCHIPS_y$) is increased (Table 8.9).

Sawing and chipping cost remain unchanged (see Methods section), however due to the reduced recovery of flitch and the increased volume of wood chips being pulped, the costs of pulping, bleaching and newsprint production were increased as *TAP* increased by 10% (Table 8.10). A 10% increase in *TAP* decreases the *Net Present Value* of the production enterprise by $41, resulting in a *Profitability Index* of –0.07%.

Table 8.9- The effect of a 10% trait increase on enterprise wood flows, where "base" values refer to the wood flows before an increase in TAP, "new" values are inclusive of a 10% increase in TAP, and the effected values are highlighted in red.

wood flow (per hectare)		T1 (15 years)		T2 (20 years)		CF (25 years)		Total		unit
		base	new	base	new	base	new	base	new	
delivered volume (incl. bark)	*VOLTOTDEL*	108.7		130.4		434.8		673.9		m3/ha
bark volume	*VOLBARK*	8.7		10.4		34.8		53.9		m3/ha
havested volume (under bark)	*VOLHARV*	100.0		120.0		400.0		620.0		m3/ha
chipped flitch volume	*VOLCHIPFL*	0.0		18.0	17.7	48.0	47.3	66.0	65.0	m3/ha
sawn flitch volume	*VOLSAWNFL*	n/a	n/a	n/a	n/a	80.0	79.0	80.0	79.0	m3/ha
pulp chip volume	*VOLTMPCHIP*	100.0		98.9	99.2	263.8	265.4	462.8	464.7	m3/ha
thermo-mechanical pulp mass	*MASSTMP*	34.2		39.2	39.3	114.0	114.7	187.4	188.2	ODt/ha
newsprint furnish	mass sum of	65.8		74.1	74.3	212.9	214.2	352.8	354.3	ODt/ha
newsprint	*MASSNEWS*	59.2		66.7	66.8	191.7	192.8	317.5	318.9	ODt/ha
newsprint (area)	*AREANEWS*	1.32		1.48	1.49	4.26	4.28	7.06	7.09	m^2 ($x10^6$)
thermo-mechanical pulp	*MASSTMP*	34.2		39.2	39.3	114.0	114.7	187.4	188.2	ODt/ha
cold caustic soak pulp	*MASSCCS*	14.3		16.3	16.4	47.5	47.8	78.1	78.4	ODt/ha
recycled fibre pulp	*MASSRCF*	8.6		9.8	9.8	28.5	28.7	46.8	47.0	ODt/ha
chemical kraft pulp	*MASSKRA*	5.2		4.8	4.8	11.6	11.6	21.6	21.7	ODt/ha
clay filler	*MASSFIL*	3.5		4.0	4.0	11.4	11.5	18.9	19.0	t/ha

Table 8.10- The effect of a 10% trait increase on costs and returns, where "base" values refer to the cost/return before an increase in TAP, "new" values are inclusive of a 10% increase in TAP, and the effected values are highlighted in red.

cost/return item	Total (P_{PV}/ha) base	new	change
growing cost	$16,873		
harvesting cost	$12,368		
transport cost	$7,943		
debarking cost	$7,783		
chipper/canter cost	$44,523	$44,593	$70
sawing cost	$4,400		
pulping cost	$50,774	$50,961	$187
bleaching cost	$52,345	$52,545	$200
newsprint cost	$129,939	$130,424	$486
total costs	**$326,948**	$327,890	$942
flitch value	$33,804	$33,347	-$457
newsprint value	$358,214	$359,572	$1,358
total returns	**$392,018**	$392,919	$901
returns minus costs (P_{PV})	**$65,070**	$65,029	-$41
profitability index (PI)	**19.90%**	19.83%	-0.07%

8.4.1.6 Basic Density

An increase of 10% in basic density corresponds to an increase of 40 kg/m^3. The primary effect of an increase in *DEN* is to increase *PWDEN* (the basic density of pulpwood chips) which, in turn, decreases the energy required to refine an OD tonne of pulpwood chips and hence decreases the overall pulping costs. Also, as *PWDEN* is increased, the mass of TMP and newsprint produced is increased (Table 8.11).

Basic density also affects the final newsprint strength properties (see Methods section). A 10% increase in basic density increases the newsprint tear strength by 0.58 mNm^2/g but slightly decreases the newsprint tensile strength by 0.52 Nm/g at each harvest. The combined result of these antagonistic effects is that more kraft pulp must be added to the pulp furnish (Table 8.11) to increase the newsprint strength to a desired level and hence an increase in newsprint costs.

Green density, the green weight per unit of green volume, is also increased when basic density is increased, thus increasing the green weight of the wood harvested per hectare and increasing the costs of harvesting and transport per hectare (Table 8.12).

The effect of a 10% increase in basic density is to increase the present value of profit by $14,137 and *Profitability Index* by 3.32%.

Table 8.11- The effect of a 10% trait increase on enterprise wood flows, where "base" values refer to the wood flows before an increase in DEN, "new" values are inclusive of a 10% increase in DEN, and the effected values are highlighted in red.

wood flow (per hectare)		T1 (15 years)		T2 (20 years)		CF (25 years)		Total		unit
		base	new	base	new	base	new	base	new	
delivered volume (incl. bark)	*VOLTOTDEL*	108.7		130.4		434.8		673.9		m3/ha
bark volume	*VOLBARK*	8.7		10.4		34.8		53.9		m3/ha
havested volume (under bark)	*VOLHARV*	100.0		120.0		400.0		620.0		m3/ha
chipped flitch volume	*VOLCHIPFL*	0.0		18.0		48.0		66.0		m3/ha
sawn flitch volume	*VOLSAWNFL*	n/a	n/a	n/a	n/a	80.0		80.0		m3/ha
pulp chip volume	*VOLTMPCHIP*	100.0		98.9		263.8		462.8		m3/ha
thermo-mechanical pulp mass	*MASSTMP*	34.2	37.8	39.2	42.7	114.0	123.5	187.4	204.0	ODt/ha
newsprint furnish	mass sum of	65.8	71.9	74.1	79.9	212.9	228.4	352.8	380.1	ODt/ha
newsprint	*MASSNEWS*	59.2	64.7	66.7	71.9	191.7	205.5	317.5	342.1	ODt/ha
newsprint (area)	*AREANEWS*	1.32	1.44	1.48	1.60	4.26	4.57	7.06	7.60	m^2 ($x10^6$)
thermo-mechanical pulp	*MASSTMP*	34.2	37.8	39.2	42.7	114.0	123.5	187.4	204.0	ODt/ha
cold caustic soak pulp	*MASSCCS*	14.3	15.8	16.3	17.8	47.5	51.4	78.1	85.0	ODt/ha
recycled fibre pulp	*MASSRCF*	8.6	9.5	9.8	10.7	28.5	30.9	46.8	51.0	ODt/ha
chemical kraft pulp	*MASSKRA*	5.2	5.0	4.8	4.3	11.6	10.3	21.6	19.7	ODt/ha
clay filler	*MASSFIL*	3.5	3.9	4.0	4.3	11.4	12.3	18.9	20.4	t/ha

Table 8.12- The effect of a 10% trait increase on costs and returns, where "base" values refer to the cost/return before an increase in DEN, "new" values are inclusive of a 10% increase in DEN, and the effected values are highlighted in red.

cost/return item	Total (P_{PV}/ha) base	new	change
growing cost	$16,873		
harvesting cost	$12,368	$12,555	$187
transport cost	$7,943	$8,064	$121
debarking cost	$7,783		
chipper/canter cost	$44,523		
sawing cost	$4,400		
pulping cost	$50,774	$52,311	$1,537
bleaching cost	$52,345	$57,089	$4,743
newsprint cost	$129,939	$137,513	$7,575
total costs	**$326,948**	$341,110	$14,163
flitch value	$33,804		
newsprint value	$358,214	$386,513	$28,299
total returns	**$392,018**	$420,317	$28,299
returns minus costs (P_{PV})	**$65,070**	$79,206	$14,137
profitability index (*PI*)	**19.90%**	23.22%	3.32%

8.4.1.7 Basic Working Stress

Increasing the basic working stress of rough green timber flitches increases average flitch value by $16 per cubic metre of rough green flitch (see Methods section). Assuming an average *BWS* of 6.5MPa, a 10% increase in *BWS* (0.65MPa) increases flitch value by $10 per cubic metre of flitch.

Wood-flows are unchanged by increased *BWS* (hence a table of changes in wood-flows is not presented for *BWS*) and the only change in the production system is in the value of the flitch sold per hectare (Table 8.13). A 10% increase in *BWS* increases profit by $1624 per hectare and profitability index by 0.50% per hectare (Table 8.13).

Table 8.13- The effect of a 10% trait increase on costs and returns, where "base" values refer to the cost/return before an increase in BWS, "new" values are inclusive of a 10% increase in BWS, and the effected values are highlighted in red.

cost/return item	Total (P_{PV}/ha) base	new	change
growing cost	$16,873		
harvesting cost	$12,368		
transport cost	$7,943		
debarking cost	$7,783		
chipper/canter cost	$44,523		
sawing cost	$4,400		
pulping cost	$50,774		
bleaching cost	$52,345		
newsprint cost	$129,939		
total costs	**$326,948**		
flitch value	$33,804	$35,428	**$1,624**
newsprint value	$358,214		
total returns	**$392,018**	**$393,642**	**$1,624**
returns minus costs (P_{PV})	**$65,070**	**$66,694**	**$1,624**
profitability index (*PI*)	**19.90%**	**20.40%**	**0.50%**

8.4.1.8 Tracheid Length

An increase of 10% in tracheid length corresponds to an increase of 0.25 mm. The primary effects of an increase in *LEN* is to decrease the energy required to refine an OD tonne of pulpwood chips and hence decrease the overall pulping costs. Tracheid length also affects the final newsprint strength properties (see Methods section). A 10% increase in tracheid length increases the newsprint tear strength by 0.33 mNm^2/g and the tensile strength by 0.51 Nm/g. The combined result of these effects is that more kraft pulp must be added to the pulp furnish to increase the newsprint strength to a desired level and hence an increase in newsprint costs.

Wood-flows are mostly unchanged by increased *LEN* except that now, as less kraft pulp is required, the mass of pulp furnish is reduced and subsequently the mass of filler (which is assumed to be added to the pulp furnish on a percentage basis) is reduced. This leads to a decrease in the mass of newsprint produced on a per-hectare basis (Table 8.14). A 10% increase in *LEN* increases present value profit by $3,195 per hectare and *Profitability Index* by 1.46% per hectare (Table 8.15).

Table 8.14- The effect of a 10% trait increase on enterprise wood flows, where "base" values refer to the wood flows before an increase in LEN, "new" values are inclusive of a 10% increase in LEN, and the effected values are highlighted in red.

wood flow (per hectare)		T1 (15 years)		T2 (20 years)		CF (25 years)		Total		unit
		base	new	base	new	base	new	base	new	
delivered volume (incl. bark)	*VOLTOTDEL*	108.7		130.4		434.8		673.9		m3/ha
bark volume	*VOLBARK*	8.7		10.4		34.8		53.9		m3/ha
havested volume (under bark)	*VOLHARV*	100.0		120.0		400.0		620.0		m3/ha
chipped flitch volume	*VOLCHIPFL*	0.0		18.0		48.0		66.0		m3/ha
sawn flitch volume	*VOLSAWNFL*	n/a	n/a	n/a	n/a	80.0		80.0		m3/ha
pulp chip volume	*VOLTMPCHIP*	100.0		98.9		263.8		462.8		m3/ha
thermo-mechanical pulp mass	*MASSTMP*	34.2		39.2		114.0		187.4		ODt/ha
newsprint furnish	mass sum of	65.8	65.0	74.1	73.2	212.9	210.4	352.8	348.7	ODt/ha
newsprint	*MASSNEWS*	59.2	58.5	66.7	65.9	191.7	189.4	317.5	313.8	ODt/ha
newsprint (area)	*AREANEWS*	1.32	1.30	1.48	1.46	4.26	4.21	7.06	6.97	m^2 ($x10^6$)
thermo-mechanical pulp	*MASSTMP*	34.2		39.2		114.0		187.4		ODt/ha
cold caustic soak pulp	*MASSCCS*	14.3		16.3		47.5		78.1		ODt/ha
recycled fibre pulp	*MASSRCF*	8.6		9.8		28.5		46.8		ODt/ha
chemical kraft pulp	*MASSKRA*	5.2	4.5	4.8	4.0	11.6	9.2	21.6	17.7	ODt/ha
clay filler	*MASSFIL*	3.5	3.5	4.0	3.9	11.4	11.3	18.9	18.7	t/ha

Table 8.15- The effect of a 10% trait increase on costs and returns, where "base" values refer to the cost/return before an increase in LEN, "new" values are inclusive of a 10% increase in LEN, and the effected values are highlighted in red.

cost/return item	Total (P_{PV}/ha) base	new	change
growing cost	$16,873		
harvesting cost	$12,368		
transport cost	$7,943		
debarking cost	$7,783		
chipper/canter cost	$44,523		
sawing cost	$4,400		
pulping cost	$50,774	$47,617	-$3,157
bleaching cost	$52,345		
newsprint cost	$129,939	$125,722	-$4,216
total costs	**$326,948**	$319,575	-$7,373
flitch value	$33,804		
newsprint value	$358,214	$354,036	-$4,178
total returns	**$392,018**	$387,840	-$4,178
returns minus costs (P_{PV})	**$65,070**	$68,265	$3,195
profitability index (PI)	**19.90%**	21.36%	1.46%

8.4.1.9 Tracheid Coarseness

An increase in tracheid coarseness of 10% (i.e. increasing tracheid coarseness from 0.50 to 0.55 mg/m) reduces the opacity of the newsprint sheet by 0.54% (Equation 8.24) and thus increases the amount of filler added to the forming newsprint sheet on the paper machines (Table 8.16). Although increasing the cost of producing an OD tonne of newsprint, the addition of more filler increases the mass of newsprint produced per hectare and thus increases the income derived from the sale of newsprint (Table 8.17). A 10% increase in *CRS* increases present value profit by $13 per hectare but decreases the *Profitability Index* by 0.09% per hectare.

Table 8.16- The effect of a 10% trait increase on enterprise wood flows, where "base" values refer to the wood flows before an increase in CRS, "new" values are inclusive of a 10% increase in CRS, and the effected values are highlighted in red.

wood flow (per hectare)		T1 (15 years)		T2 (20 years)		CF (25 years)		Total		unit
		base	new	base	new	base	new	base	new	
delivered volume (incl. bark)	*VOLTOTDEL*	108.7		130.4		434.8		673.9		m3/ha
bark volume	*VOLBARK*	8.7		10.4		34.8		53.9		m3/ha
havested volume (under bark)	*VOLHARV*	100.0		120.0		400.0		620.0		m3/ha
chipped flitch volume	*VOLCHIPFL*	0.0		18.0		48.0		66.0		m3/ha
sawn flitch volume	*VOLSAWNFL*	n/a	n/a	n/a	n/a	80.0		80.0		m3/ha
pulp chip volume	*VOLTMPCHIP*	100.0		98.9		263.8		462.8		m3/ha
thermo-mechanical pulp mass	*MASSTMP*	34.2		39.2		114.0		187.4		ODt/ha
newsprint furnish	mass sum of	65.8	66.0	74.1	74.4	212.9	213.8	352.8	354.2	ODt/ha
newsprint	*MASSNEWS*	59.2	59.4	66.7	66.9	191.7	192.4	317.5	318.8	ODt/ha
newsprint (area)	*AREANEWS*	1.32	1.32	1.48	1.49	4.26	4.28	7.06	7.08	m^2 ($x10^6$)
thermo-mechanical pulp	*MASSTMP*	34.2		39.2		114.0		187.4		ODt/ha
cold caustic soak pulp	*MASSCCS*	14.3		16.3		47.5		78.1		ODt/ha
recycled fibre pulp	*MASSRCF*	8.6		9.8		28.5		46.8		ODt/ha
chemical kraft pulp	*MASSKRA*	5.2		4.8		11.6		21.6		ODt/ha
clay filler	*MASSFIL*	3.5	3.8	4.0	4.3	11.4	12.3	18.9	20.4	t/ha

Table 8.17- The effect of a 10% trait increase on costs and returns, where "base" values refer to the cost/return before an increase in CRS, "new" values are inclusive of a 10% increase in CRS, and the effected values are highlighted in red.

cost/return item	Total (P_{PV}/ha) base	new	change
growing cost	$16,873		
harvesting cost	$12,368		
transport cost	$7,943		
debarking cost	$7,783		
chipper/canter cost	$44,523		
sawing cost	$4,400		
pulping cost	$50,774		
bleaching cost	$52,345		
newsprint cost	$129,939	$131,404	$1,466
total costs	**$326,948**	$328,413	$1,466
flitch value	$33,804		
newsprint value	$358,214	$359,666	$1,452
total returns	**$392,018**	$393,470	$1,452
returns minus costs (P_{PV})	**$65,070**	$65,056	-$13
profitability index (PI)	**19.90%**	19.81%	-0.09%

8.4.1.10 Wood Brightness

Increasing the brightness (BRG_{NEW}) of plantation grown radiata pine wood reduces the consumption of relatively expensive chemicals utilised in the peroxide bleaching process (including hydrogen peroxide itself and caustic). An increase of 10%, which corresponds to a 5% increase in wood brightness leads to an increase of 2.6% (from 59.9% to 62.5%) of newsprint sheet brightness (PB_{NEW}). This, in turn leads to a decrease of around 13% in peroxide and caustic consumption and reduces overall bleaching costs by $4,331 per hectare (Table 8.19)

Wood-flows are unchanged by increased *BRG* and the only change in the production system is in the cost of bleaching per hectare just discussed, increasing the overall enterprise *Profitability Index* by 1.61% (Table 8.19).

Table 8.19- The effect of a 10% trait increase on costs and returns, where "base" values refer to the cost/return before an increase in BRG, "new" values are inclusive of a 10% increase in BRG, and the effected values are highlighted in red.

cost/return item	Total (P_{PV}/ha) base	new	change
growing cost	$16,873		
harvesting cost	$12,368		
transport cost	$7,943		
debarking cost	$7,783		
chipper/canter cost	$44,523		
sawing cost	$4,400		
pulping cost	$50,774		
bleaching cost	$52,345	$48,014	-$4,331
newsprint cost	$129,939		
total costs	**$326,948**	$322,616	-$4,331
flitch value	$33,804		
newsprint value	$358,214		
total returns	**$392,018**		
returns minus costs (P_{PV})	**$65,070**	$69,401	$4,331
profitability index (*PI*)	**19.90%**	21.51%	1.61%

8.4.2 Economic weights

The changes in overall enterprise long-term profit (P_{PV}) and long-term profitability (*PI*) associated with a 10% increase in each trait and a unit increase in each trait (i.e. the economic weight) are presented in Table (8.20).

Table 8.20- Increment in *Net Present Value* (P_{PV}) and *Profitability Index* (*PI*) associated with a 10% trait increase (changes are specified in absolute units of P_{PV} and absolute percentage point units of *PI*), and economic weights (W_{NPV} and W_{PI}, the change in P_{PV} and *PI* respectively for a unit increase after Equations 8.29 and 8.30) for each trait.

trait	units	mean	10% trait increase	change in economics due to 10% trait increase		Economic Weight	
				$W_{(10\%)\,NPV}$	$W_{(10\%)\,PI}$	W_{NPV}	W_{PI}
MAI	m3/ha/yr	20	2	$8,418	0.64%	$4,209	0.33%
BRK	%	8	0.8	-$190	-0.07%	-$239	-0.09%
BIX	cm	5	0.5	-$1,396	-0.43%	-$2,792	-0.85%
SWE	mm/m	3	0.3	-$25	-0.04%	-$82	-0.14%
TAP	mm/m	5	0.5	-$41	-0.07%	-$82	-0.14%
DEN	kg/m3	400	40	$14,137	3.32%	$347	0.08%
BWS	MPa	6.5	0.65	$1,624	0.50%	$2,499	0.76%
LEN	mm	2.5	0.25	$3,195	1.46%	$12,741	5.87%
CRS	mg/m	0.5	0.05	-$13	-0.09%	-$269	-2.05%
BRG	%	50	5	$4,331	1.61%	$866	0.32%

Anthony and Reece (1989), in discussing the application of economic indicators to long-term investment decision analysis, conclude that when choosing between investment options, the profitability index is an optimum indicator. If the net present value method is used, the present value of the income and costs from the "base" situation may not be compared directly with the present value of the income and costs of the "new" situation (i.e. the production system following trait-change) unless the investments are of an analogous scale (Anthony and Reece 1989). Hence the economic weight for any given trait calculated under the *Net Present Value* method can not be directly compared with other economic weights if the effect of that unit trait change alters the wood flow within the currently defined enterprise. For example, increasing *MAI* by 10% alters the wood flow throughout the production enterprise, resulting in a present value profit of $8,418 (Table 8.20). However, increasing *MAI* by 10% results in a 10% increase in wood volume, resulting in a 10% increase in costs and a 10% increase in income (i.e. the enterprise has simply been scaled up by 10%). Some account of the size of the discounted profit to the amount of money risked needs to be adjusted for. The profitability index provides this, by simply dividing the present value profit by the present value costs (the amount of investment). Indeed, Brascamp *et al.* (1985) demonstrated that when production system profit is set to zero the various economic weight perspectives become equal. Further, Smith *et al.* (1986) demonstrated that economic value calculated as incremental profit could be an overestimate of the true economic advantage of genetic improvement if a component of incremental profit could be attributed to an increase in the scale of the operation. Therefore the most appropriate calculation of economic advantage from trait

improvement is considered here to be that based upon profitability index (following the advice of Anthony and Reece 1989) and further discussion will focus only on economic weights calculated using this methodology.

The values of a 10% increase in each trait as depicted in Table (8.20), while more indicative of the value of trait improvement than economic weights, do not take account of differences in the exploitable genetic variation between traits. For example, there is considerably more exploitable genetic variation in growth rate (e.g. Carson 1991) than there appears to be in wood property traits such as basic density and tracheid coarseness (Nyakuengama *et al.* 1997, Shelbourne *et al.* 1997) and tracheid length and wood brightness (Matheson *et al.* 1997). Similarly these estimates do not account for the genetic correlations between traits. What these values do indicate, is the relative value of improvement in one trait over another. Therefore Table (8.20) suggests basic density to be the most important trait ($W_{(10\%)PI}$ = 3.32%) being approximately twice as important as wood brightness ($W_{(10\%)PI}$ = 1.61%) and two-and-a-half times more important than tracheid length ($W_{(10\%)PI}$ = 1.46%) when aiming to increase the economic gain of the enterprise currently defined (Table 8.20). Basic working strength, growth rate (*MAI*) and branch index appear to have a moderate effect, while bark percentage, stem taper, stem sweep and tracheid coarseness appear to have a relatively minor affect on enterprise profitability compared with the other traits investigated here (Table 8.20).

The bias of economic values estimated from the *Net Present Value* (P_{PV}) method, associated with not accounting for the rescaling of the enterprise due to a change in wood flows (see Smith *et al.* 1986), can be clearly observed in Table (8.20). For example, the economic value measured by the *Net Present Value* method for a 10% increase in *MAI*, ranks this trait as the second most important overall, just over half as important as basic density when aiming to maximise economic gain. However, the 'true' economic gain, as estimated by $W_{(10\%)PI}$ suggests that *MAI* is ranked as only the fourth most important trait – around five times less important than basic density, when taking into account the 10% increase in the scale of the enterprise due to the 10% increase in *MAI*.

Based on the economic weights for profitability index derived in Table (8.20), the breeding objective function (as first defined by Hazel in 1943 as "aggregate genotype") may be written as:

$$\begin{aligned} H_{PI} = {} & 0.33(\Delta MAI) - 0.09(\Delta BRK) - 0.85(\Delta BIX) - 0.14(\Delta SWE) - 0.14(\Delta TAP) \\ & + 0.08(\Delta DEN) + 0.76(\Delta BWS) + 5.87(\Delta LEN) - 2.05(\Delta CRS) + 0.32(\Delta BRG) \end{aligned} \qquad (8.33)$$

where:

- H_{PI} is the aggregate value of the genotype in absolute percentage units of profitability index (W_{PI} for each trait are estimated following Equation 8.30);
- ΔMAI is the genotype's breeding value for mean annual increment in $m^3/ha/yr$;
- ΔBRK is the genotype's breeding value for mean percentage bark volume, expressed as a percentage of the total volume (wood plus bark);
- ΔBIX is the genotype's breeding value for branch index in cm;
- ΔSWE is the genotype's breeding value for stem sweep in mm/m;
- ΔTAP is the genotype's breeding value for stem taper in mm/m;
- ΔDEN is the genotype's breeding value for basic density in kg/m^3;
- ΔBWS is the genotype's breeding value for the basic working stress of timber flitch, expressed in MPa;
- ΔLEN is the genotype's breeding value for mean tracheid length in mm;
- ΔCRS is the genotype's breeding value for mean tracheid coarseness in mg/m;
- ΔBRG is the genotype's breeding value for mean wood brightness, expressed in terms of percentage reflectance at 457nm; and
- breeding values are assumed to be expressed as deviations from the population mean.

The "value" of a given genotype, in terms of the profitability index, may be estimated from Equation (8.32). For example, a genotype with breeding values (expressed as deviations from the population mean) of: *MAI* 1 $m^3/ha/yr$; *BRK* 0.5%; *BIX* 0.2cm; *SWE* –0.2mm; *TAP* –0.1mm; *DEN* 20 kg/m^3; *BWS* 0.1MPa; *LEN* 0.2 mm; *CRS* 0.02 mg/m; and *BRG* 3%, has an aggregate profitability index breeding value of 3.92%.

8.4.3 Interpreting Profitability Index

Profitability Index is defined as the ratio of total profit and total costs, and represents, in the current context, the percentage of total costs that may be expected as profit (Equation 8.30). The estimates of relative economic values due to an increase in each trait of 10% in Table (8.22) are useful but do not really show

the advantage (in terms of real gain) of increasing one trait over another in the most amenable terms. Therefore, an interpretation of the values presented in Table (8.22) is provided. The present value, at the time of plantation establishment, of the future gain associated with one year's planting for an enterprise can be estimated from the expected change in *Profitability Index* (ΔPI) following:

$$VALUE = \frac{\Delta PI}{PI_{BASE}} \times P_{PV}\left(1+\frac{d}{100}\right)^{-t_{CF}} \times ANAREA \qquad (8.34)$$

where:

- *VALUE* is the annual value to the enterprise discounted to the time of plantation establishment of an estimated change in profitability index;
- PI_{BASE} is the *Profitability Index* of the enterprise prior to tree improvement (19.9%; Table 7.6);
- P_{PV} is the future value of total profit per hectare before improvement ($65,070; Table 7.6);
- d is the annual discount rate (5%, Table 7.1);
- t_{CF} is the age of clearfall harvest (25 years, Table 7.2); and
- *ANAREA* is the annual establishment area, assumed to be 3,000 hectares.

The value to the enterprise of a 1% increase in profitability index over a single 3000 hectare establishment, discounted to the time of establishment (Equation 8.34) is $2.9 million.

The present value of all future gain, assuming that gain occurs annually for the foreseeable future is estimated following:

$$FUTGAIN = VALUE \times \left[1-\left(1+\frac{d}{100}\right)^{-n}\right] \times \left(\frac{100}{d}\right) \qquad (8.35)$$

where:

- *FUTGAIN* is the present value of all future gain, assuming that "all future" refers to at least 70 years (n).

The present value of all future gain of a 1% increase in *Profitability Index* (equivalent to an annual gain of $2.9 million for a 3000 hectare annual establishment program) is $56 million.

Table 8.21- Increment in Profitability Index (*PI*) associated with a 10% trait increase (changes are specified in absolute percentage point units of *PI*), the annual value to the enterprise of a 10% trait increase, discounted to the time of plantation establishment ($VALUE_{(10\%)}$) and the present value of all future gain, assuming the gain is annually occurring for the foreseeable future ($FUTGAIN_{(10\%)}$).

trait	units	mean	10% trait increase	change in economics due to 10% trait increase		
				$W_{(10\%)\,PI}$	$VALUE_{(10\%)}$	$FUTGAIN_{(10\%)}$
MAI	m3/ha/yr	20	2	0.25%	1.91 M	37 M
BRK	%	8	0.8	-0.09%	-0.22 M	-4 M
BIX	cm	5	0.5	-0.85%	-1.23 M	-24 M
SWE	mm/m	3	0.3	-0.14%	-0.12 M	-2 M
TAP	mm/m	5	0.5	-0.14%	-0.20 M	-4 M
DEN	kg/m3	400	40	0.05%	9.27 M	180 M
BWS	MPa	6.5	0.65	0.76%	1.43 M	28 M
LEN	mm	2.5	0.25	5.87%	4.25 M	82 M
CRS	mg/m	0.5	0.05	-2.05%	-0.30 M	-6 M
BRG	%	50	5	0.32%	4.63 M	90 M

Table (8.21) suggests that if, for example, a forest grower was to improve *MAI* by 10% (2m^3/ha/yr) across a 3000 hectare plantation area, then the economic benefit (*VALUE*) to that forest grower would be around $1.9M discounted back to the present day. An enterprise planting this number of hectares per year in the foreseeable future stand to gain $37M in present value terms.

8.4.4 Sensitivity Analysis

The economic value of improving basic density is most sensitive to the assumed newsprint value ($IRNEWS_y$) across harvesting operations (Table 8.22). Indeed, this parameter appeared to be a key driver in overall enterprise profitability (see Chapter 7- Table 7.8) and also appeared to be an important variable driving the economic value associated with a number of traits including *MAI*, *BRK*, *BIX*, *SWE*, *TAP* and *BRG*. The second most important parameter determining the economic value of basic density is an intercept term in the model relating specific refining energy consumption to pulpwood density (Equation 8.14) – a parameter which was investigated in Chapter 4, but based on a pilot laboratory scale study and may need verifying on a larger mill scale. The economic value of tracheid length also appeared to be sensitive to this parameter and to another variable in the same model (Table 8.22). The cost of electrical power per kilowatt hour consumed was shown to be the fourth most sensitive parameter for basic density and tracheid length, which are the traits with a direct influence on the specific energy consumed during the thermomechanical refining process. The economic value of bark percentage and tracheid coarseness also showed sensitivity to changes in the cost

of power. The economic value of growth rate (*MAI*) was most sensitive to (in order of descending significance) the value of newsprint, the total under-bark clearfall harvest volume, the value of sawn flitch and the discount rate. These are a consequence of the increased wood flow changes to the system- a greater mass of newsprint and sawn flitch is produced due to increases in the under-bark harvested volume ($VOLHARV_y$), with this volume being greatest at clearfall harvest. Because growth rate effects the plantation establishment costs, the discount rate becomes important as these costs must be compounded to the end of the rotation.

The impact of bark percentage on the overall enterprise profitability and the way it was modelled (i.e. impacting only on the relatively minor harvesting and transporting costs) caused the economic value of this parameter to tend to be most sensitive to those parameters which showed the greatest impact on the production system overall, regardless of trait change (e.g. value of newsprint and the cost of power). The green density of bark (*GDB*) and the cost of debarking (*BARKRATE*) were the second and third most sensitive parameters overall. The green density of bark was assumed to be 0.7 tonnes per cubic metre of bark, which was based on local knowledge (John Simpson, *pers. comm.*), however this has not been rigorously tested.

Similar to bark thickness, the economic value due to a 10% increase in the coarseness of a tracheid was negligible, but most sensitive to the cost of filler and a model parameter determining the handsheet opacity directly from wood coarseness (Table 8.22). These would seem self-explanatory, however the third and fourth most sensitive parameters – *IRNEWS* and *POWER* are again a consequence of the negligible effect of this trait on the overall enterprise profitability, and the sensitivity is 'swamped' by those parameters with greatest affect on this overall profitability.

The most important input parameters for the value of improving *SWE* and *TAP* are the assumed impacts on the recovery of sawn flitch, *SWESAWNREC* and *TAPSAWNREC* respectively (Table 8.22), assumed to be 0.5 and 0.1 percent of recovered volume per mm/metre respectively. The relative lack of value in improving either trait (Table 8.22) will change little with even considerable changes in these assumptions.

Table 8.22- Sensitivity analysis for economic weights by trait: Spearman's Rank Order Correlation between the estimated profitability index economic weight and the three most correlated production system and trait change input parameters. All presented correlation coefficients are significantly different to zero at p=0.0001. Model parameters presented in "bold" are those most correlated with the economic value of each trait.

Economic Weight (W_{PI})		Correlated production system input parameter	Rank Order Correlation
MAI	*IRNEWS*	value of newsprint ($/OD tonne)	0.56
	VOLHARVCF	total under-bark volume at clearfall harvest (m^3/ha)	-0.44
	SAWNFLRATE	the value of sawn flitch ($/$m^3$ flitch)	0.21
	DISCOUNT	annual discount rate (%)	0.21
BRK	*IRNEWS*	value of newsprint ($/OD tonne)	-0.43
	GDB	bark green density (t/m^3)	-0.35
	BARKRATE	cost of debarking a cubic metre of green log	-0.27
	POWER	cost of refining energy ($/kWhr)	0.22
BIX	*SAWNRECCF*	the recovery of sawn flitch at clearfall (%/m^3/ha)	-0.62
	BIXSAWNFL	effect of *BIX* on average value of sawn flitch ($/$m^3$/cm)	0.36
	IRNEWS	value of newsprint ($/OD tonne)	0.23
	BIXCHIPFL	effect of *BIX* on average value of chipped flitch ($/$m^3$/cm)	0.22
SWE	*SWESAWNREC*	effect of *SWE* on sawn flitch recovery (%/mm/m)	-0.61
	IRNEWS	value of newsprint ($/OD tonne)	0.34
	CHIPFLRATE	the value of chipped flitch ($/$m^3$ flitch)	-0.33
	SAWNFLRATE	the value of sawn flitch ($/$m^3$ flitch)	-0.21
TAP	*TAPSAWNREC*	effect of *TAP* on sawn flitch recovery (%/mm/m)	-0.61
	IRNEWS	value of newsprint ($/OD tonne)	0.33
	CHIPFLRATE	the value of chipped flitch ($/$m^3$ flitch)	-0.32
	SAWNFLRATE	the value of sawn flitch ($/$m^3$ flitch)	-0.21
DENS	*IRNEWS*	value of newsprint ($/OD tonne)	0.68
	SEC INTERCEPT	SEC_{NEW}="**3748**"-(1.29 x LEN_{BASE} x $PWDEN_{NEW}$)	-0.33
	NEWSREC	newsprint mill recovery (%/OD tonne TMP)	0.31
	POWER	cost of refining energy ($/kWhr)	-0.27
BWS	*BWSSAWN*	effect of BWS on average value of sawn flitch	0.67
	BWSCHIP	effect of BWS on average value of chipper canter flitch	0.55
	SAWNFLREC	recovery of sawn flitch at clearfall (%/m^3/ha)	0.31
	CHIPFLREC	recovery of chipped flitch at clearfall (%/m^3/ha)	0.24
LEN	*KRARATE*	cost of kraft pulp ($/OD tonne)	0.43
	SEC VARIABLE 1	SEC_{NEW}=3748-("**1.29**" x LEN_{NEW} x $PWDEN_{BASE}$)	0.42
	SEC INTERCEPT	SEC_{NEW}="**3748**"-(1.29 x LEN_{NEW} x $PWDEN_{BASE}$)	-0.33
	POWER	cost of refining energy ($/kWhr)	0.30
CRS	*FILRATE*	cost of clay filler ($/OD tonne)	-0.62
	OP VARIABLE	OP_{NEW}=88.27-("**10.71**" x CRS_{NEW})	-0.36
	IRNEWS	value of newsprint ($/OD tonne)	0.21
	POWER	cost of refining energy ($/kWhr)	0.24
BRG	*PER CONSTANT*	PER=(PB_{REQ} - PB_{BASE})/"**4.10**"	-0.68
	IRNEWS	value of newsprint ($/OD tonne)	0.31
	CAU VARIABLE	CAU=0.05 + ("**0.77**" x PER)	0.28
	PERRATE	cost of hydrogen peroxide ($/tonne)	0.19

The most important input parameter for the value of improving *BIX* is the recovery of sawn flitch at clearfall harvest, assumed to be 20% of the under-bark harvested volume (Table 8.22). Due to the effect of branch size on the value of sawn flitch, the economic sensitivity of *BIX* to this parameter may not seem surprising. The second and fourth most sensitive input parameters are the assumed effect of *BIX*

on sawn flitch and chip canter flitch value respectively. These key parameters were predicted using the SAWMOD simulation software (Whiteside and McGregor 1986) designed for use in New Zealand and may differ for radiata pine grown and processed elsewhere. The value for both of these parameters is -$19 per cubic metre of sawn or chipped flitch per centimetre of *BIX* – doubling this parameter (an extreme) results in a doubling of the expected gain from improvement of *BIX* (to a *PI* increase of –0.92% for a 10% *BIX* increase), which is still lower than the value of improving basic density (3.51%), wood brightness (1.48%) and tracheid length (1.13%). Similarly, the two most sensitive input parameters to the economic weight derived for basic working stress were the assumed effects of *BWS* on sawn and chipped flitch value respectively. Both key parameters were derived from predictions made using New Zealand's empirically derived SAWMOD sawing simulation software (Whiteside and McGregor 1986).

The economic value for improving wood brightness is most sensitive to an input model parameter relating the percentage peroxide required to achieve a required minimum pulp handsheet brightness (Table 8.22). Indeed, this parameter (termed "*PER* constant" in Table 8.22) was shown to be an important determinant of enterprise profitability overall (see Chapter 7- Table 7.8), and the nature of the parameter (i.e. being the sole denominator of the margin of pulp handsheet brightness to satisfy) is such that even a small variation in value will have a far reaching effect on overall enterprise profitability by dramatically altering the cost of bleaching. The third most sensitive input parameter was another model parameter (termed "*CAU* variable" in Table 8.22) which relates the amount of caustic required to the amount of peroxide bleach added. This situation closely models reality, as increasing amounts of caustic must be added to maintain the pH as increasing amounts of peroxide are added to bleach the TMP.

8.5 General Discussion

Other biological traits, not modelled in the present chapter have been implicated to have an affect on the profitability of forestry enterprises aimed at producing a number of products. For example spiral grain is a common feature of conifers, and a pronounced feature of juvenile wood in radiata pine (Sorensson *et al.* 1997). Severe spirality, and the tangential shrinkage that thereby affects longitudinal shrinkage in the lumber, will cause lumber to twist excessively during drying. Sorensson *et al.* (1997) describe twist as a serious economic problem facing the modern forest industry which is exacerbated by reductions in the rotation length and thus an increased proportion of juvenile wood in the annual cut. Microfibril angle has also been implicated in influencing checking and timber stiffness and

strength (Bendtsen and Seft 1984), and thus timber value (Walker and Butterfield 1995). Most distortion of timber during drying is due to irregular longitudinal shrinkage (Shelbourne *et al.* 1997). Radiata pine normally shrinks about 2, 4 and 0.1% in tangential, radial and longitudinal directions respectively (Shelbourne *et al.* 1997). Distortion is caused by high spiral grain angles (away from the longitudinal axis of the board) combined with high and irregular longitudinal shrinkage, which may be caused by compression wood with high microfibril angles (Harris 1977). However due to a lack of available relationships, the enterprise defined here did not include a component which allowed changes in spiral grain and microfibril angle to influence the recovery of seasoned sawn timber from rough green sawn flitch.

The trait changes resulting from tree breeding are expected to be relatively small, and to this end the economic weights included in the definition of the current breeding objective will enable tree breeders to include economic information in assessment and selection strategies. The underlying methodology of Hazel (1943), however, assumes that the economic advantage of improvement is linear and additive (Chapter 6) but this has been shown, in the context of forest tree breeding, to possibly be an imprecise assumption (Greaves 1997).

8.5.1 The value of an increase in growth rate (MAI)

The benefit of increasing MAI was assumed to be derived from an increase in volume produced per hectare without appreciably changing growing costs (Greaves, *in review*). Increasing *MAI* was assumed to not influence any components of the processing economics, it was simply assumed that this reduced the growing costs relative to processing costs. As discussed by Greaves (*in review*), this might be achieved silviculturally if establishment stocking is increased in direct proportion with *MAI* (i.e. a 10% increase in *MAI* requires a 10% increase in establishment stocking with a factored increase in establishment costs – Equation 8.3). As rotation length is assumed to remain unchanged, the trees grow to the same size as unimproved stock, but there are 10% more of the "same" trees per hectare at harvests.

The method used to model growth in the current work (as first described by Greaves *in review*) is not, however, the way that most forest growers would choose to exploit faster growing genotypes. In general, forest growers choose to maintain or reduce stocking and to harvest their forest earlier as the trees grown are now reaching a desirable size in a shorter time (Klemperer 1994). However Greaves (*in review*) states that this may result in confounding changes to the overall enterprise economics. Younger radiata pine trees may have lower density (Uprichard 1980) and reduced timber strength and stiffness (Kennedy 1995). These changes could have occurred in the absence of genetic improvement by planting unimproved

material at a wider spacing and reducing rotation length. Further, Nyakuengama (1997) showed age related changes (in both variance components and parental breeding values) for a number of microstructural wood traits, including fibre size, wall thickness and coarseness. Thus, the economic advantage of increasing *MAI* would be exaggerated if the analysis assumed either shorter rotations or the production of larger trees over the same rotation. The assumption that increasing growth allows the grower to produce proportionally more roundwood of the same "type" is described in detail in Greaves (*in review*) and is a simplifying assumption that aims to minimise the confounding effects of a silvicultural change. This is an area of potential improvement in the current model. There is, conversely, ample evidence that illustrates that there can be premium prices paid for logs in larger log size classes and also indications that additional yields of wood can be achieved without affecting growing costs appreciably (and with minor effects on transport costs). Also, given that stands are well-stocked (i.e. normal high survival), it is mensurationally unlikely that the stand can carry more trees of similar size distributions.

Another parameter which has not yet been discussed and is of huge importance to a pulp mill is the issue of wood variation. This aspect of variation should be included in any future modeling attempts. Tree improvement leads to greater uniformity which has been demonstrated as having a very significant impact on the efficient conversion of wood to paper (Dr. Bob Cox[1] *pers. comm.*).

A concept introduced in Chapter 6 was that of re-optimisation of the production system enterprise. Ladd and Gibson (1978) and Amer *et al.* (1994) argue that the enterprise may need to be reoptimised as a result of genetic improvement and that the economic value of this improvement must account for any resulting change in the enterprise's operations. In the context of forestry and forest products, reoptimisation may involve altering the rotation length or silvicultural management of growing plantations. Any further work in the area of defining breeding objectives for forestry enterprise systems should extend the multi-trait modeling process to examine the re-optimisation of systems of forest management and utilisation, however this is beyond the scope of the present thesis.

[1] Dr. Robert Cox, Research Manager, Fletcher Challenge Paper Boyer Mill.

8.6 Conclusion

The overall profitability of the vertically integrated production enterprise defined in Chapter 7 can be influenced by changing the characteristics of the grown plantation wood. If growth rate can be increased (without change in any other tree characteristics), the growing costs can be reduced in comparison to processing costs: a 10% increase in growth rate will increase overall enterprise profitability index by 0.64%. Increasing wood basic density by 10% had the largest effect on the defined enterprise production system and will increase the overall profitability index by 3.32%. A 10% increase in wood brightness and tracheid length resulted in increases in overall enterprise profitability indices of 1.61% and 1.46% respectively. Increasing *BWS* by 10%, increased profitability by 0.50%, however the impact of this trait would be expected to rise for a production system with a greater emphasis on sawlog production. Other traits examined, with less impact on the defined production enterprise and their respective enterprise profitability index changes with 10% trait improvement are: bark percentage -0.07%, branch index -0.43%, stem sweep –0.04%, stem taper –0.07%, and tracheid coarseness –0.09%.

The breeding objective was defined as a linear combination of the derived economic weights:

$$H_{PI} = 0.33(\Delta MAI) - 0.09(\Delta BRK) - 0.85(\Delta BIX) - 0.14(\Delta SWE) - 0.14(\Delta TAP) + 0.08(\Delta DEN) + 0.76(\Delta BWS) + 5.87(\Delta LEN) - 2.05(\Delta CRS) + 0.32(\Delta BRG)$$

where:

- H_{PI} is the aggregate genotypic breeding value for profitability index and *MAI*, *BRK*, *BIX*, *SWE*, *TAP*, *DEN*, *BWS*, *LEN*, *CRS*, *BRG* are the estimated breeding values (as deviations from the population mean) of biological traits of the genotype.

Chapter 9

Genetic parameter estimates of tracheid transverse dimensions, wood density and wood brightness in radiata pine

9.1 General Introduction

The aim of any breeding program is to maximise the incidence of desirable characteristics and minimise the incidence of undesirable characteristics in the population under consideration (Wade 1990). These characteristics are usually defined by their economic importance (Moav 1971). In response to this, the previous two chapters have followed the methodology of Ponzoni and Newman (1989) in defining a breeding objective function to derive economic weights. However, economic weights alone do not provide an adequate indication of the value of each trait to a tree breeder (Borralho *et al.* 1993). The usefulness of a trait in the context of breeding is a function of the economic weight, the exploitable genetic variation, and the correlations with other traits of economic importance (Weller 1994). For example, genetic gain due to selection on the breeding objective traits directly can be determined following White and Hodge (1989):

$$GAIN = i\left(\mathbf{w}'\mathbf{A}'\mathbf{P}^{-1}\mathbf{A}\mathbf{w}\right)^{0.5} \qquad (9.1)$$

where:

- **A** is the additive covariance matrix between breeding objective traits;
- **w** is a vector of economic weights for all objective traits
- **P** is the phenotypic covariance matrix relating breeding objective traits.

However, this would assume that selection is applied to each trait in the breeding objective directly at rotation age (25 years), which is the age at which the economic weights are defined. Indeed, for tree improvement programs, selection is most often at an age considerably earlier than rotation age (Cotterill and Dean 1990) and the breeding objective traits are often indirectly assessed (Woolaston and Jarvis 1995). For example, measurements of diameter and pilodyn penetration (selection criteria) are often used in forestry as predictors for Mean Annual Increment and Basic Density (breeding objective traits) respectively. In this case, the **A** matrix defined in Equation (9.X) above would be an additive covariance matrix relating selection criteria to the objective traits and the **P** matrix a phenotypic matrix now relating selection traits. In this case therefore, the genetic correlations between breeding objective traits are not so much an issue as the relationships between selection criteria and all the objective traits. However, genetic and phenotypic variance estimates and thus the heritability of breeding objective traits are still required. The ultimate aim of this chapter, therefore, is to produce a set of variance and heritability estimates for the breeding objective traits examined in Chapter 8. This is achieved by means of:

- a small study estimating genetic parameters for a number of wood microstructure traits, wood density, tracheid length and wood brightness in radiata pine; and
- a review of recent literature to tabulate published genetic information on each of the breeding objective traits identified.

The list of genetic parameters produced from these analyses is used in the next chapter to estimate the gain from selection on a number of criteria (as measured currently by the STBA[4]) aimed at improving the traits directly in the breeding objective (as identified in Chapter 8).

9.2 Experimental

9.2.1 Introduction

The suitability of a tree for different end uses has been shown to be determined not only by its morphological characteristics such as, for example growth, branch size and stem sweep, but also by its intrinsic wood properties (Shelbourne *et al.* 1997),

[4] STBA – Southern Tree Breeding Association

particularly those of its component tracheids (for example tracheid length and tracheid coarseness). Approximately 90% of coniferous wood, by volume, is composed of tracheids (Nyakuengama *et al.* 1999) and consequently physical wood traits such as wood density and wood brightness depend on the diameter, wall thickness and abundance of tracheids. However, these tracheid properties and dimensions are difficult and costly to measure, indicating why there are so few studies on these traits (see Shelbourne *et al.* 1997 and Nyakuengama *et al.* 1999). This study investigated the variability of wood density, tracheid cross-sectional dimensions, tracheid coarseness and specific surface area in radiata pine using the SilviScan-1 device (Evans 1994, Evans *et al.* 1995). It also examines the variability of wood brightness and tracheid length in the same families, providing the first indication of the genetic relationship between these traits.

9.2.2 Trial Site, Design and Wood Cores

The trial used for the current wood property analysis is located at West Takone on land owned by AFH[5] – APPM[6] and then by NET[7] at Latitude 41° 11' E and 145° 32' S. It is located on the 1:100000 map series Hellyer at grid reference 773 398. The elevation of the trial is 480m (asl) and the soil type is a mesotrophic red ferrosol, similar to a krasnozem type.

The trial consisted of 10 replicates of 47 open-pollinated families (44 experimental families and 3 control families) planted in five tree plots planted in August of 1981 as part of a cooperative effort between CSIRO Forestry and Forest Products, Forestry Tasmania and NET (formerly AFH). Genetic material was originally planted at four spacings: 3m x 2m, 2m x 1m, 1m x 1m and 0.5m x 1m. Cores (pith to bark) for the 3m x 2m spacing were taken in January 1995 from two trees per plot in each plot of replicate 5. Cores (pith to bark) from the 2m x 1m spacing were also taken from two trees per plot in each plot of replicate 3. The two closer spacings were not sampled due to the high level of mortality by the time of sampling, which may have confounded the results (Matheson[8] *pers comm.*). Cores for both spacings were soaked in ethanol for around 5 minutes within six hours of collection, wrapped in cellophane and refrigerated.

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[5] AFH – Australian Forest Holdings

[6] APPM – Australian Pulp and Paper Mills

[7] NET – North Eucalypt Technologies

[8] Colin Matheson – CSIRO Forestry and Forest Products

9.2.3 Analysis of Wood Cores

SilviScan, an automated scanning x-ray microdensitometer and image analyser (Evans *et. al* 1995) was used to measure tracheid radial and tangential profiles across each ring and then measure wood density profiles by x-ray densitometry (see also Shelbourne *et al.* 1997, Nyakuengama *et al* 1999). A number of variables were measured directly with other values derived from these (basal-area-weighted values were calculated for specified groups of rings, using the outermost ring as the baseline), as shown in Table (9.1).

Tracheid length and wood brightness were measured at Fletcher Challenge Paper's Boyer mill. A portion of each wood core sample were digested in peracetic acid following the technique of Cox *et al.* (1996). A Kajaani FS200 fibre analyser was then used to determine the length weighted average length of tracheids in solution. The remainder of each core sample was ground into a fine powder and analysed on an Elrepho 2000 spectrometer at the region 457nm (visible, blue) of the light spectrum to obtain estimates of wood brightness (light reflectance at 457nm, expressed as a percentage). Overall means and standard deviations (including information from the experimental families only) for tracheid length and wood brightness are shown in Table 9.1

Table 9.1- Overall means for each trait analysed and their respective standard deviations.

Measured Traits	Comments	Units	No. Cores	No. Fams	Mean	S.D.
Tracheid Length (L)	peracetic acid digestion	mm	175	44	1.72	0.15
Radial Tracheid Diameter (R)	pith to bark direction	µm	176	44	32.09	1.89
Tangential Tracheid Diameter (T)	parallel to rings	µm	176	44	26.60	0.94
Wood Density (D)	air dry, conditioned to 23^{0}C.. ..and 50% relative humidity	kg.m^{-3}	94	44	346.30	29.30
Wood Brightness (B)	grinding into a powder	%	88	44	35.74	2.29
Derived Variables	**Comments**	**Units**	**No. Cores**	**No. Fams**	**Mean**	**S.D.**
Tracheid External Perimeter (P)	P = 2(R+T)	µm	176	44	117.40	4.96
Tracheid Coarseness (C)	C=R T D (mass per unit length)	µg.m^{-1}	176	44	346.30	29.90
Tracheid Wall Thickness (W)	=P/8 - 1/2	µm	176	44	2.14	0.15
Specific Surface Area (S)	=P/C (excluding lumen)	m^2.kg^{-1}	176	44	348.40	23.10

9.2.4 Statistical Analysis

Variance and covariance components, heritabilities and genetic correlations were estimated using ASREML (Gilmour *et al.* 1995, 1997). ASREML is a recently developed software which performs restricted maximum likelihood analyses of a

wide range of models, using the named average information algorithm and sparse matrix technology. Variance components for each trait were calculated following:

$$\mathbf{y} = \mathbf{i} + \mathbf{Xs} + \mathbf{Zf} + \mathbf{e} \qquad (9.2)$$

where:

- **y** is the vector of N observations for wood traits;
- **s** is the vector for the effect of spacing (assumed fixed);
- **f** is the vector for the family (or GCA) effects; and
- **X** and **Z** are matrices for the spacing and GCA[9] effects respectively.

The expected mean and variances of the parameters y, s, f and e are as follows:

$$E\begin{bmatrix} y \\ e \\ f \end{bmatrix} = \begin{bmatrix} Xs \\ 0 \\ 0 \end{bmatrix}, \qquad Var\begin{bmatrix} y \\ e \\ f \end{bmatrix} = \begin{bmatrix} V & R & ZG_f \\ R & R & 0 \\ G_f Z' & 0 & G_f \end{bmatrix} \qquad (9.3)$$

where:

- $V = R + ZG_fZ'$;
- $R = \bigoplus_{j=1}^{m} R_{oj}$, with m = number of records;
- $G_f = I_f \otimes G_{of}$; and
- G_{of} = variance-covariance matrix for the family effect,;
- R_{oj} = residual covariance matrix for tree j;
- $\otimes$ = Kronecker product;
- $\oplus$ = direct sum.

Narrow sense heritabilities were calculated from the variance components, according to the formula:

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[9] General combining ability – The mean performance of a parent expressed as a deviation from the overall mean of crosses, i.e. experimental mean (Falconer and Mackay 1996)

$$\hat{h}^2 = \frac{4\sigma^2_{fam}}{\left(\sigma^2_{fam} + \sigma^2_{res}\right)} \quad (9.4)$$

where:

- σ^2_{fam} is the between-family variance component
- σ^2_{res} is the residual variance component in the design strata based on equation (9.1).

Standard errors for heritabilities were estimated from the post processing facility of ASREML (Gilmour *et al.* 1995, 1997).

Genetic and phenotypic correlations between respective wood traits were estimated from the variance and covariance components as:

$$r_G = \frac{\text{cov}(fam_x, fam_y)}{\sqrt{\sigma^2_{fam_x}\sigma^2_{fam_y}}} \quad (9.5)$$

where

- r_G is the genetic correlation between wood traits x and y, and
- cov(fam_x,fam_y) is the covariance between family effects for trait x and y.

9.2.5 Results and Discussion

Overall means for tracheid length, radial diameter, tangential diameter, coarseness, wall thickness, specific surface, perimeter, wood density and brightness and their standard deviation are given in Table 9.1.

Variance components, narrow sense heritabilities and their approximate standard errors for each trait are given in Table 9.2.

Table 9.2- Estimates of family (σ^2_{fam}), residual (σ^2_{res}) and total phenotypic (σ^2_p) variances (% of total phenotypic shown in parentheses) and corresponding heritability estimate (standard error shown in parentheses) for each trait analysed.

Trait	σ^2_{fam}	σ^2_{res}	σ^2_p	h^2 (s.e.)
Length	0.002	0.019	0.021	0.40
	(9.52)	(90.48)		(0.36)
Radial Diameter	0.689	2.790	3.479	0.79
	(19.80)	(80.2)		(0.39)
Tangential Diameter	0.084	0.788	0.872	0.39
	(9.63)	(90.37)		(0.39)
Coarseness	145.5	763.6	909.1	0.64
	(16.01)	(83.99)		(0.38)
Wall Thickness	0.004	0.020	0.024	0.66
	(16.66)	(83.34)		(0.38)
Specific Surface	84.53	452.2	536.7	0.63
	(15.74)	(84.26)		(0.41)
Perimeter	4.38	19.59	23.98	0.73
	(18.31)	(81.69)		(0.39)
Density	164.8	697.7	862.5	0.76
	(19.11)	(80.89)		(0.40)
Brightness	0.739	4.532	5.271	0.56
	(14.02)	(85.98)		(0.49)

Differences between families were shown to account for between 9.5 and 19.1% (Table 9.2) of the total phenotypic variation, once the effects of the two different spacing regimes had been accounted for. Estimates of narrow sense heritability were generally very high compared to reported heritability estimates for growth and form traits (e.g. Burdon *et al.* 1992, Dean *et al.* 1983). However, genetic parameter estimates in this study were associated with large standard errors probably resulting from the small number of cores measured overall. None of the heritability estimates shown in Table 9.2 were significant in respect of being greater than the corresponding value of two standard errors of each estimate (a rule of thumb, indicating a significant degree of difference from zero). Nevertheless, heritabilities were shown to range from 0.39 for tangential diameter to 0.79 for radial diameter. Radial diameter, tangential diameter, length, density and brightness were all measured independently, while the remainder of the traits- coarseness, wall thickness, specific surface and perimeter were derived from these. The heritability of these derived traits showed intermediate values depending on their derivation, as noted by Shelbourne *et al.* (1997). In general, heritability estimates were much lower than those calculated by Shelbourne *et al.* (1997) and Nyakuengama *et al.* (1999) – see Table 9.3. These differences are likely due, at least in part, to the

imprecision of current estimates based on the very small sample size used (i.e. 176 cores) but also the larger genetic base (47 parents). In addition, individuals are present in the current analysis which contain genes derived from clone 80055 parents (for more details regarding the unique properties of this clone, see Nyakuengama 1997). The presence of progeny 80055 has been suggested by Nyakuengama (1999) as the main factor for the different genetic parameter estimates between his study and an earlier study by Shelbourne *et al.* (1997).

Another difference between the current study and that of Shelbourne *et al.* (1997) was that all growth rings were sampled compared with only the outer 8 to 13 rings (mature wood) being sampled in the latter. Nevertheless, there is broad agreement across all three studies in regard to the strong genetic control of most tracheid properties. The studies of Shelbourne *et al.* (1997) and Nyakuengama *et al.* (1999), however did not include genetic parameter estimates of tracheid length and wood brightness. The heritability estimates of tracheid length and wood brightness reported by Matheson *et al.* (1997) and McGranahan (*in prep.*) were lower than those reported in the present study, most likely due to the reasons just discussed.

Table 9.3- Estimates of heritability for tracheid transverse dimensions, wood density and wood brightness in four recent studies in radiata pine, where: THESIS represents estimates also listed in Table 9.2 for the current study, SHEL97 estimates published in Shelbourne *et al.* (1997), NYAK99 estimates published in Nyakuengama *et al.* (1999), McGR20 estimates published in McGranahan (PhD Thesis, *in prep.*), and MATH97 estimates published in Matheson *et al.* (1997).

Trait	h^2				
	THESIS	SHEL97	NYAK99	McGR20	MATH97
Tracheid length (L)	0.40	-	-	0.30	0.31
Radial Diameter (R)	0.79	1.09	1.77	-	-
Tangent. Diameter (T)	0.39	0.53	1.80	-	-
Coarseness (C)	0.64	0.82	0.92	0.15	-
Wall Thickness (W)	0.66	0.77	0.50	-	-
Specific Surface (S)	0.63	0.79	0.46	-	-
Perimeter (P)	0.73	0.97	2.04	-	-
Density (D)	0.76	0.87	1.29	0.07	-
Wood Brightness (B)	0.56	-	-	0.30	0.09

The genetic and phenotypic correlations between each trait analysed are given in Table 9.4, overleaf.

Table 9.4- Estimated genetic (above diagonal) and phenotypic (below diagonal) correlations. Significant correlations are depicted as either: *(p<0.05), **(p<0.01), or *(p<0.001).**

Trait	L	R	T	C	W	S	P	D	B
Length (L)		0.42	0.84	0.75	0.68	-0.62	0.61	0.77	1.02
Radial Diameter (R)	0.30***		0.91	0.70	0.38	-0.39	0.99	0.07	0.30
Tangent. Diameter (T)	0.47***	0.76***		0.63	-0.28	-0.08	0.95	0.03	0.48
Coarseness (C)	0.60***	0.64***	0.37**		0.56	-0.54	0.42	-0.18	-0.66
Wall Thickness (W)	0.45***	0.09^{ns}	-0.11^{ns}	0.70***		-0.78	0.14	0.65	-0.25
Specific Surface (S)	-0.44***	-0.24**	-0.15*	-0.66***	-0.88***		-0.08	-0.53	0.27
Perimeter (P)	0.50***	0.87***	0.83***	0.51***	0.09^{ns}	-0.04^{ns}		-0.09	0.54
Density (D)	0.16*	-0.25**	-0.31***	0.09^{ns}	0.77***	-0.66***	-0.20**		-0.09
Brightness (B)	0.21**	0.14^{ns}	0.06^{ns}	-0.36***	0.01^{ns}	0.07^{ns}	0.09^{ns}	-0.18*	

The estimates of genetic and phenotypic correlations between tracheid and wood properties were generally consistent, as expected when estimates of heritability are high, with phenotypic correlations lower than genetic (Table 9.4). Measures of tracheid size (perimeter, radial and tangential diameters) were strongly, positively correlated ($r_G \rightarrow 1$). Density (at breast height) was negatively correlated with radial and tangential tracheid diameters, as shown by Shelbourne *et al.* (1997) and Nyakuengama *et al.* (1999) indicating a strong inverse relationship between density and tracheid size. Similar relationships were found between basic density and tracheid diameter (r_g =-0.3) Otegbeye and Kellison (1980) for loblolly pine and between basic density and tracheid width (r_g=-0.58) by Zobel *et al.* (1960). As discussed by Nyakuengama *et al.* (1999), some studies have reported an inverse relationship between density and radial lumen diameter (Otegbeye and Kellison 1980, Larson 1973) however lumen diameter was not directly measured in the current study.). The strong positive correlation between density and wall thickness found in the present study would not seem surprising as the latter was derived partly from the former. Tracheid coarseness is a compound trait, depending on both tracheid size and the thickness of tracheid walls. This compound nature is reflected in the genetic correlations, with a negative relationship shown between coarseness and density, but positive relationships between coarseness and wall thickness and size traits. Nyakuengama *et al.* (1999) suggest that fibre size and wall thickness are under different physiological controls, and the fact that no obvious association (genetic or phenotypic) was evident in Table (9.4) between these two properties would support this view. Indeed overall, the phenotypic relationships between the SilviScan density and tracheid properties were consistent with those reported in other SilviScan studies (Evans *et al.* 1995, Shelbourne *et al.* 1997 and Nyakuengama *et al* 1999). The genetic correlation between tracheid length and wood brightness resulted in a value exceeding 1 (Table 9.4), reflecting

the poor precision of the current analysis, however the phenotypic correlation was also positive and significant indicating that trees containing, on average, longer tracheids also had brighter wood. There was also evidence of a weak negative relationship between wood brightness and density at the phenotypic and genetic level (Table 9.4), similar to earlier findings in loblolly pine by Wilcox (1973). It is possible that wood brightness (or percentage reflectance at 457nm) is affected by the amount and distribution of lignin on the wood tracheids (Wilcox 1973), and clearly more work needs to be undertaken in this area.

9.2.6 Conclusion

The SilviScan-1, an automated image analyser and X-ray microdensitometer provided a continuous record on the variation of wood density and wood microstructure traits (tracheid cross-sectional dimensions, tracheid coarseness and specific surface area) in breast height radial increment cores (Nyakuengama *et al.* 1999). In addition tracheid length and wood brightness were measured, providing the first estimates of the relationships between these traits and those measured by the SilviScan-1 device.

Estimates of heritability for all wood traits were high indicating that selection for these traits could lead to significant genetic change, however these estimates were also associated with large standard errors (most likely due to the small number of core samples included in the study). Tracheid size was inversely correlated with density and positively correlated with tracheid coarseness. This agrees with the results obtained by Nyakuengama *et al.* (1999) and confirm that tracheid coarseness, like density, is a complex trait under two separate wood properties namely, tracheid size and tracheid wall thickness (Nyakuengama *et al.* 1999). Wood brightness showed a significant phenotypic relationship with tracheid coarseness and tracheid length, but seemed more or less independent of all the fundamental tracheid properties analysed here.

9.3 Tabulated summary of genetic variation and heritability estimates for traits in the objective

Table 9.5 (overleaf) attempts to summarise some recent published estimates of heritability and the coefficient of genetic variation for each trait in the breeding objective. Based on all of the evidence reviewed and any other unverified evidence available, an assumed value for each parameter is produced (Table 9.5- far right-hand column) for use in the next chapter.

Table 9.5- Published estimates of heritability and genetic coefficient of variation (unless indicated otherwise) for each trait and the value assumed. All values represent published estimates for radiata pine unless specified.

trait	sources of information	Assumed	
		CV_G	h^2
MAI	• Lausberg and Donaldson (unpubl. data - cited by Shelbourne (1997)): tree volume at age 16: CV_p=18% - assuming h^2 0.15, CV_a = 7% • 6%: dbh, age 10 (Greaves *et al.* 1987), h^2 = 0.26 • 7.8%: dbh, age 10 (White *et al.* 1992b), • h^2 (volume) 0.19 (Cotterill and Dean 1990), h^2 (dbh) 0.10 (Carson 1991), h^2 (vol) 0.18 (Matheson and Raymond 1984), h^2 (vol) 0.21 (Cotterill and Zed) at various ages between 5 & 16	7%	0.20
bark percentage	• CV_p = 19% bark thickness, h^2 0.38 (Wei and Borralho 1997) • CV_p = 17% relative bark thickness, h^2 0.35 (Wei and Borralho 1997) for blue gum. • CV_a= 3.6% relative bark thickness asuming h^2 0.34 (Kelly 1997)	4%	0.35
branch index	• Beauregard *et al.* (1997) age 28: branch index CV_p=24% - assuming h^2 0.2: CV_a = 11% • 14%: branch quality (1-6 score), age 10 (White *et al.* 1992b) • 20%: branch score (1-6 score), age 10 (Greaves *et al.* 1987) asuming h^2=0.34 • h^2 0.25: branch quality (1-6 score) – Cotterill and Dean (1990), h^2 0.44: branch score– Matheson and Raymond (1984) at age 9	11%	0.30
sweep	• 14%: straightness score (1-6 score), age 10 (White *et al.* 1992b) • 14%: stem score (1-6 score), age 10 (Greaves *et al.* 1987) assuming h^2 = 0.20 • h^2 0.38 (stem straightness) Matheson and Raymond (1984) • h^2 0.27 (mean of published estimates) Cotterill and Dean (1990)	14%	0.25
taper	• h^2 no known estimates, assumed to be of the same magnitude as growth and sweep • CV_g assumed by Greaves (1999) of 4%	4%	0.25
density	• 4%: density, age 5 (Greaves *et al.* 1987), h^2 0.39 • 4%: SilviScan density age 23 (Nyakuengama *et al.* 1999) • Shelbourne *et al.* (1997a) age 25; CV_p 7.7% - assuming h^2 0.87: CV_a = 5% • Hinds and Reid (1957) (cited by Walford, 1991): CV_p density 9% - assuming h^2 0.4: CV_a = 6% • 7.4%: density, age 14 (this chapter): CV_p 16.9% h^2=0.76 • h^2 0.64 (mean of published estimates) Cotterill and Dean (1990) • h^2 0.49 Nicholls *et al.* (1980) at age 5	4%	0.60
BWS	• Hinds and Reid (1957) (cited by Walford, 1991): CV-MOR small-clear samples 24%; CV-MOE small-clear samples 18% - assuming h^2 0.4: CV_a = 12% • Beauregard *et al.* (unpubl. data - cited by Shelbourne (1997)) age 28: mean min. MOE of sawn-timber 6.83MPa; CVp 7.5%	5%	0.40
tracheid length	• 5.2%: length, age 14 (this chapter): CV_p 16.9% assuming h^2 0.4 • 4.63%: length, age 16 (Matheson *et al.* 1997) assuming h^2 0.31 • 4.5%: Scots pine, age 11 (Hannrup and Ekberg 1998) assuming h^2 is 0.31; 5.2%, age 31 assuming h^2 is 0.48.	5%	0.35
tracheid coarseness	• 7%: SilviScan coarseness, age 14 (this chapter): CV_p 17.4% - assuming h^2 0.64 • 8.2%: SilviScan coarseness, age 25, CV_p 9% assuming h^2 0.82 (Shelbourne *et al.* 1997) • SilviScan coarseness Nyankuengama *et al.* (1999) CV_p 9% assuming h^2 0.92 • Kajaani coarseness, age 10 (McGranahan 2000), CV_a 3.2%, assuming h^2 0.21	5%	0.50
wood brightness	• 8%: brightness, age 14 (this chapter): CV_p 14.8%, h^2 0.56 • 2.3%: brightness, age 10 (McGranahan 2000), h^2 0.30 • 4.6%: brightness, age 16 (Matheson *et al* 1997), h^2 0.10 • 4.1%: brightness (Wilcox 1975)- assuming h^2 0.28	4.5%	0.30

*estimates in red ink were derived from Table (9.2) earlier in this chapter

Chapter 10

Selection index coefficients for STBA breeding values for an objective which maximises the profitability of a vertically integrated enterprise producing timber flitch and newsprint

Chapter 10 has been published as an industry technical report:
Chambers P.G.S and Greaves B.L. (1999): Selection index coefficients for STBA breeding values for an objective which maximises the profitability of a vertically integrated enterprise producing timber flitch and newsprint.

10.1 Introduction

Southern Tree Breeding Association Technical reports TR92-02 and TR92-04 (White *et al.* 1992a and 1992b) list Expected Breeding Values (EBVs) for 1212 first generation parents and 1152 second-generation selections respectively. The EBVs listed are expressed as a percentage difference between the additive genetic worth of the individual and the assumed unimproved population mean, both at an assumed selection age of 10 years. EBVs are listed for diameter at 1.3m (dbh), branch quality score, and stem straightness score for all individuals, and basic density for a few individuals.

The aggregate genetic worth of a genotype can be estimated from the sum of the products of the estimated breeding values and the selection index coefficients:

$$V = b_{DBH}\,EBV_{DBH} + b_{BRANCH}\,EBV_{BRANCH} + b_{STEM}\,EBV_{STEM} + b_{DENS}\,EBV_{DENS} \qquad (10.1)$$

where:

- V is the aggregate genetic value expressed in the units of the economic objective;
- b_{DBH} is the selection coefficient of *DBH*, and EBV_{DBH} is the estimated breeding value of *DBH* and the other terms similarly for the other selection traits.

In matrix notation, Equation 10.1 may be expressed as:

$$V = \mathbf{b}'\mathbf{g} \qquad (10.2)$$

where:

- **b** is a vector of selection index coefficients ([sx1] in the case of *s* selection traits); and
- **g** is a vector of estimated breeding values ([sx1] also).

Two indices for STBA breeding values: a multi-purpose index and a high growth index (Table 10.1 – after White *et al.* 1992a) do not have weights for density, and were derived to maximise trait gain. The multi-purpose index (MP_IND) gave almost equal percentage gains in all three traits, while high growth index (GR_IND) gave near maximal gains in growth within the constraint that gains could not be negative for the other two traits (White *et al.* 1992a).

Table 10.1- Selection indices for STBA radiata pine breeding values (after White *et al.* 1992a).

selection trait	STBA trait	STBA multi-purpose (MP_IND)	STBA high growth (GR_IND)
dbh10	BVDBH	0.6667	0.8333
branch score	BVBRANCH	0.2222	0.125
stem score	BVSTEM	0.1111	0.0417

The index weights listed in Table 10.1 were developed by White *et al.* (1992a) on the basis that there was a lack of economic data to guide the choice of weights to place on each selection trait.

Economic weights for an economic improvement objective have, however, been recently derived in Chapter 8 for a notional integrated forestry and forest products enterprise which grows radiata pine without pruning, harvests, transports and processes to structural timber flitch and newsprint. With this information now available, the selection index coefficients can alternatively be derived from known economic weights for objective traits after (Schneeberger *et al.* 1992):

$$\mathbf{b} = \mathbf{G}_{11}^{-1}\mathbf{G}_{12}\mathbf{w} \qquad (10.3)$$

where:

- $\mathbf{G}_{11}$ is a genetic covariance matrix relating the *s* selection traits (a [sxs] matrix);
- $\mathbf{G}_{12}$ is a genetic covariance matrix relating the *s* selection traits to the *o* objective traits (a [sxo] matrix); and
- $\mathbf{w}$ is a vector of economic weights of the *o* objective traits (a [ox1] vector).

Another consideration, is that the genetic relationship between the selection traits at an early age and the objective traits at a later age contains a component of age-age correlation. Lambeth (1980) proposed a model for prediction of age-age correlations based upon the logarithm of the ratio of ages:

$$r = \beta \ln\left(\frac{\mathbf{early-age}}{\mathbf{later-age}}\right) + c \qquad (10.4)$$

where:

- β-symbol is a coefficient which dictates the rate of decline in age-age correlation with reduction in the ratio of ages (i.e an increase in the age difference); and
- *c* is a constant that equates to the correlation when there is no difference between the ages - theoretically this should be equal to unity but arguably could be different to unity on the basis that the predictive region of the model is at greater age differences.

In summary then, the derivation of selection index coefficients for STBA EBVs must consider the following issues:

- genetic variation for each selection trait;
- genetic relationship between selection traits;

- age-age correlations for selection traits between selection age and the ages when economic advantage is realised;
- genetic relationship between selection traits and economic objective traits; and
- genetic variation within each economic objective trait.

Using the economic weights derived in Chapter 8, this report assumes values for all the required parameters and estimates selection index coefficients for the STBA EBVs. As many of the assumed parameters are not known without error, sensitivity analysis were used to identify critical assumptions.

10.2 Methods

10.2.1 Method overview

The following procedure was adopted:

- define selection traits for each population
- define genetic parameters of selection traits
- define age-age correlation relationships for selection traits
- define economic objective (economic weights)
- define genetic correlations between selection traits
- define genetic correlations between selection traits and objective traits
- estimate selection index coefficients
- undertake sensitivity analysis to identify critical assumptions
- compare selection indices

10.2.2 Selection Traits

STBA breeding values are tabulated in STBA Technical Reports TR92-02 (White *et al.* 1992a) and TR92-04 (White *et al.* 1992b) for dbh, branch quality score, stem

straightness score and density. The number, range, variation and relationship between these traits for the STBA EBVs are summarised in Table 10.2.

Table 10.2: STBA EBVs - number, minimum, maximum, standard deviation and simple correlation between traits

selection trait	count	min	max	stddev	correlations between EBVs*			
		(% above unimproved)			DBH	BRANCH	STEM	DENS
DBH	2414	-10.3	19.1	4.0	1.00			
BRANCH	2414	-19.4	34.6	7.4	0.09	1.00		
STEM	2414	-19.3	38.6	8.8	0.27	0.43	1.00	
DENS	511	-9.9	7.7	2.3	-0.30	-0.02	-0.15	1.00

* Correlations between DENS and other traits calculated over 511 trees with DEN EBVs
* Correlations between DBH, BRANCH and STEM calculated over all trees

10.2.3 Age-age correlations for selection traits

The assumed coefficients of *LAR* for the selection traits (β in Equation 10.4), and the estimated age-age correlations (after Equation 10.4) are presented in Table (10.3).

Table 10.3- Assumed coefficients of *LAR* by selection trait (after Appendix 10.5.3), and derived age-age correlations between selection age (10 years) and relevant production system operation ages (after Equation 10.4).

selection trait	coefficient of *LAR*	derived age-age correlation between selection age and operation age			
		EST age 0	T1 age 15	T2 age 20	CF age 25
dbh	0.25	1.00	0.90	0.83	0.77
branch score	0.25	1.00	0.90	0.83	0.77
stem score	0.25	1.00	0.90	0.83	0.77
density	0.05	1.00	0.98	0.97	0.95

10.2.4 Economic objective

The economic weights for an improvement objective for maximising the profitability of an enterprise which grows, harvests, transports, and processes unpruned radiata pine to make structural timber flitch and newsprint (after Chapter 8) are presented in Table 10.4.

Table 10.4- Economic weights: the change in overall enterprise Profitability Index due to a 10% trait increase, by production system operation (establishment (EST), first thinning (T1), second thinning (T2), and clearfall (CF)) and total overall (actual economic weights afterChapter 8).

trait	unit	change in overall enterprise *PI* due to trait increase of 10%				
		EST age 0	T1 age 15	T2 age 20	CF age 25	overall
MAI	m3/ha/yr	-0.08%	-0.12%	0.09%	0.77%	0.64%
bark percentage	%	0.00%	-0.02%	-0.02%	-0.04%	-0.07%
branch index	cm	0.00%	0.00%	-0.07%	-0.36%	-0.43%
stem sweep	mm/m	0.00%	0.00%	-0.01%	-0.04%	-0.04%
stem taper	mm/m	0.00%	0.00%	-0.01%	-0.06%	-0.07%
density	kg/m3	0.00%	0.91%	0.79%	1.71%	3.32%
basic working strength	Mpa	0.00%	0.00%	0.08%	0.42%	0.50%
length	mm	0.00%	0.32%	0.32%	0.80%	1.46%
coarseness	mg/m	0.00%	-0.02%	-0.02%	-0.05%	-0.09%
wood brightness	%	0.00%	0.40%	0.36%	0.83%	1.61%

10.2.5 Correlation between selection traits and objective traits

The assumed genetic variation of the economic objective traits (after Chapter 9) and correlation with selection traits (after Appendix 10.5.4) are listed in Table 10.5.

Table 10.5- Economic objective traits - assumed genetic variation (following Chapter 9 and expressed as genetic coefficient of variation, CV_G) and genetic correlation with selection traits (after Appendix 10.5.4)

trait	CV_G	genetic correlations with selection traits			
		dbh	branch score	stem score	density
MAI	7.0%	0.9	-0.1	0.2	-0.2
bark percentage	4.0%	0.35	0	0	0
branch index	14.0%	0.1	-0.9	-0.6	-0.1
stem sweep	14.0%	-0.2	-0.6	-0.9	-0.1
stem taper	4.0%	0	0	0	0
density	5.0%	-0.2	0.1	0.1	0.9
basic working strength	5.0%	-0.2	0	0	0.8
length	5.0%	-0.1	0	0	0.4
coarseness	8.0%	0	0	0	-0.1
wood brightness	4.5%	0	0	0	-0.2

10.2.6 Derivation of a selection index

Selection index coefficients for selection traits ($\mathbf{b}$), can be calculated from economic weights of objective traits ($\mathbf{w}$), if the covariances between the selection traits ($\mathbf{G}_{11}$) and the covariances between the selection traits and the objective traits ($\mathbf{G}_{12}$) are known:

$$\mathbf{b} = \mathbf{G}_{11}^{-1}\mathbf{G}_{12}\mathbf{w} \qquad (10.5)$$

where:

- the covariance elements of $\mathbf{G}_{11}$ and $\mathbf{G}_{12}$ are derived after:

$$\mathrm{cov}_{12} = r_{12}\sigma_1\sigma_2 \qquad (10.6)$$

where:

- r_{12} is the genetic correlation between the selection trait and the objective trait; and
- σ_1 and σ_2 are the genetic standard deviations of the selection trait and the objective trait respectively.

If the selection traits are at an earlier age than the objective traits the covariances in the $\mathbf{G}_{12}$-matrix should contain an effect for age-age correlation. Many of the cross correlations, for example the correlation between branch score at selection age and wood brightness at rotation age, are not well supported by evidence as the analysis stands. As such, inclusion of age-age-correlation consideration to the $\mathbf{G}_{11}$-matrix can be approximated by including an age-age correlation for the selection trait in the estimation of the covariance elements:

$$\mathrm{cov}_{12} = r_A r_{12}\sigma_1\sigma_2 \qquad (10.7)$$

where:

- cov_{12} is the genetic covariance element of the $\mathbf{G}_{12}$-matrix between a selection trait and an objective trait; and
- r_A is the age-age genetic correlation between the selection trait at selection-age and at later-age, which can be derived from the assumed relationship with *LAR* (Equation 10.4).

The net benefit of change in a selection trait is assumed to be the sum of the benefits derived from changes in the objective traits at ages of cost or income to the production system: the time of plantation establishment (*EST*); the time of first and second thinnings (*T1* and *T2*) and the time of clearfall at rotation end (*CF*). Thus:

$$\mathbf{b}_S = \mathbf{b}_{EST} + \mathbf{b}_{T1} + \mathbf{b}_{T2} + \mathbf{b}_{CF} \qquad (10.8)$$

where:

- **bs** is a vector of selection trait index coefficients derived in consideration of age-age correlations of the selection traits.

10.2.7 Sensitivity analysis of derived indices

To explore the sensitivity of the derived selection indices to variation in the assumed genetic parameters Monte-Carlo simulation was used to generate 10,000 sets of genetic parameters using @RISK software (Palisade 1997). All genetic parameters were allowed to vary with an assumed uniform probability distribution with bounds as:

- genetic coefficient of variation: assumed value ±50%;
- coefficient of *LAR* for age-age correlation: assumed value ±50%;
- genetic correlations: assumed value ±0.2; and
- economic weights: assumed value ±50%.

10.2.8 Comparison between indices

In the current work, indices were compared in three fashions:

- genetic correlation between selection indices;
- ranking of predicted breeding values; and
- expected change in objective traits for each selection index.

10.2.8.1 Genetic correlation between selection indices

The genetic correlation between selection indices was calculated using the method of Weller (1994) following:

$$r_{12} = \frac{\mathbf{b'}_1 \mathbf{G}_{11} \mathbf{b}_2}{\sqrt{(\mathbf{b'}_1 \mathbf{G}_{11} \mathbf{b}_1)(\mathbf{b'}_2 \mathbf{G}_{11} \mathbf{b}_2)}} \quad (10.9)$$

where:

- r_{12} is the genetic correlation between indices $\mathbf{b}_1$and $\mathbf{b}_2$; and
- G_{11} is the genetic covariance matrix relating the selection traits – in the current work, it represents the observed covariance between STBA estimated breeding values, calculated from Equation 10.6 and the observed correlations and variances of the breeding values (Table 10.2).

10.2.8.2 Ranking of predicted breeding values

Individual tree rankings were determined for each index following Equation 10.1. The STBA breeding values were specified in units of percent and therefore each EBV was normalised by dividing by 100:

$$V = b_{DBH} \frac{EBV_{DBH}}{100} + b_{BRANCH} \frac{EBV_{BRANCH}}{100} + b_{STEM} \frac{EBV_{STEM}}{100} + b_{DENS} \frac{EBV_{DENS}}{100} \quad (10.10)$$

10.2.8.3 Expected change in objective traits for each selection index

The expected change in the breeding objective traits for each selection index was estimated after (White and Hodge 1989):

$$\mathbf{o} = i \frac{\mathbf{G}_{12}' \mathbf{b}}{(\mathbf{b}' \mathbf{G}_{11} \mathbf{b})^{0.5}}$$

where:

- **o** is a vector of changes in the breeding objective traits due to selection pressure i applied to an aggregate tree value derived using selection index **b**;
- $\mathbf{G}_{12}$ is the genetic covariance matrix between the selection traits and the breeding objective traits; and
- $\mathbf{G}_{11}$ is the genetic covariance matrix relating the selection traits. In the current work this represents the observed covariance between STBA estimated breeding values calculated from Equation 10.6 and the observed correlations and variances of the breeding values (Table 10.2).

10.3 Results and Discussion

10.3.1 Selection index coefficients

The derived selection index coefficients are presented in Table 10.6.

Table 10.6- Selection indices derived under: (a) the age-age correlation inclusive model (Equation 10.7) and (b) the simple model (Equation 10.3), for: (1) trees with genetic values for all selection traits; and (2) trees with values for dbh, branch score and stem score only. Selection index coefficients represent the change in overall *Profitability Index* per percentage point of selection trait genetic value (EBV).

selection trait	age-age model		simple model	
	all traits	dbh branch stem	all traits	dbh branch stem
dbh	4.3%	-3.0%	4.3%	-3.1%
branch score	0.2%	1.7%	0.6%	2.2%
stem score	4.1%	3.0%	4.6%	3.6%
density	38.5%		39.2%	

Coefficients using the age-age model (Equation 10.7) are smaller than the coefficients derived using the "simple model" (Equation 10.3) because the age-age correlations which are included in this calculation are less than one, thus reducing the effective value of an increase in each selection trait.

The negative index coefficients for dbh when density is excluded as a selection trait reflect the considerable impact that density has on the production system enterprise as it is currently modeled (Chapters 7 and 8). In this case, the index is attempting to indirectly 'select' those trees with higher density, by assigning a negative weighting to dbh.

10.3.2 Sensitivity Analysis

The five most crucial input assumptions for each selection trait are presented in Table 10.7 for each of the four selection traits. Table 10.7 presents the observed Spearman's Rank Order Correlation for each of the five most critical assumptions: a higher correlation indicates that the assumption has a greater leverage on the selection index coefficient given the allowable variation in each assumption (see Section 10.2.7). Also presented in Table 10.7 are the derived leverage values for

each presented input assumption ("Δselection coeff. per Δinput par."). For example, the most critical input assumption in the estimation of the selection index coefficient for dbh is the genetic correlation between (selection trait) dbh and (selection trait) density, assumed to be –0.3. If this assumption was, instead, assumed to be higher by 0.1 (a correlation of –0.2) the selection index coefficient for dbh would be 3.5% lower.

The most critical input parameters were shown to be the genetic correlations between each selection trait and (selection trait) density (Table 10.7), and in the case of (selection trait) density, the correlation between itself and (objective trait) density. This again underlines the importance of wood density in driving the profitability of the current enterprise model.

Table 10.7- Sensitivity analysis: five most critical input parameters for each of the four selection trait coefficients. Rank order correlation (higher value indicates more critical assumption) and "Δselection coeff. per Δinput par." indicates the leverage of the input assumption on the estimated selection trait coefficient. Selection traits are represented in lower case, while objective traits are expressed in capital case (e.g. den is the selection trait, while DEN is the objective trait for density)

trait	selection coeff.	input parameter	assumed value	rank-order correlation	Δselection coeff. per Δinput par.
dbh	4.3%	correlation dbh - den	-0.3	-0.60	3.5% per 0.1
		correlation dbh - DEN	-0.2	0.38	-2.6% per 0.1
		correlation stem score - den	-0.1	0.21	1.4% per 0.1
		partial EW: MAI at clearfall	0.77%	0.18	0.8% per 1%
		coefficient of variation: dbh	7.0%	-0.15	-0.6% per 1%
branch score	0.2%	correlation branch score - den	0.1	-0.57	2.1% per 0.1
		correlation branch score - DEN	0.1	0.37	-1.5% per 0.1
		correlation stem score - den	-0.1	0.35	1.3% per 0.1
		correlation stem score - DEN	0.1	-0.23	0.9% per 0.1
		correlation branch score– BRG	0	0.16	-0.6% per 0.1
stem score	4.1%	correlation stem score – den	-0.1	-0.57	2.2% per 0.1
		correlation stem score - DEN	0.1	0.37	-1.6% per 0.1
		coeff. of variation: stem score	14.0%	-0.32	-1.3% per 1%
		correlation branch score - den	0.1	0.21	-1.2% per 0.1
		correlation stem score - BRG	0	0.14	-0.7% per 0.1
density	38.5%	correlation den - DEN	0.9	0.51	-3.7% per 0.1
		coefficient of variation: den	5.0%	-0.42	-2.6% per 1%
		coefficient of variation: DEN	5.0%	0.23	1.9% per 1%
		correlation stem score - den	-0.1	-0.12	1.2% per 0.1
		correlation den - BIX	-0.1	-0.09	1.0% per 0.1

10.3.3 Comparison of Indices

10.3.3.1 Index summary

Table 10.8 summarises seven selection indices – four derived in this report for maximising the profit of an enterprise which grows unpruned radiata pine and processes to structural flitch (for sale to a separate sawmill enterprise) and newsprint from TMP (Table 10.8); two STBA indices (Table 10.1, after White *et al.* 1992a); and one index for maximising the profit of an enterprise which grows unpruned radiata pine and processes to structural sawn timber and liner-board (after Greaves 1999).

Table 10.8- Summary of selection indices (see text for details).

trait	age-age index - all traits	simple index - all traits	age-age index	simple index	STBA multi-pulpose	STBA high growth	age-age index - all traits (Greaves 1999)
improvement objective	max profit flitch/TMP newsprint	max profit flitch/TMP newsprint	max profit flitch/TMP newsprint	max profit flitch/TMP newsprint	equivalent gain in all traits	max growth no loss in branch/stem	max profit sawn-timber/liner-board
dbh	4.44%	4.50%	-3.02%	-3.10%	0.6667	0.8333	9.85%
branch score	0.15%	0.61%	1.71%	2.20%	0.2222	0.125	6.70%
stem score	4.07%	4.66%	3.01%	3.58%	0.1111	0.0417	4.05%
density	39.27%	39.98%	0.00%	0.00%	0	0	18.91%

10.3.3.2 Genetic correlation between selection indices

Table 10.9 presents the genetic correlations between selection indices (after Equation 10.8). The correlation may be interpreted as the relative gain in profitability of one index compared to another. For example, the "simple index all traits" will provide the same gain capture as the "age-age index- all traits", however the "age-age index" (i.e. an index with no density assessments made) will provide only 31% of the gain in overall enterprise profitability as the "age-age index- all traits" as currently modelled.

Table 10.9- The genetic correlation between selection indices (see text for details).

	age-age index - all traits	simple index - all traits	age-age index	simple index	STBA multi-pulpose	STBA high growth	age-age index - all traits (Greaves 1999)
improvement objective	max profit flitch/TMP newsprint	max profit flitch/TMP newsprint	max profit flitch/TMP newsprint	max profit flitch/TMP newsprint	equivalent gain in all traits	max growth no loss in branch/stem	max profit sawn-timber/liner-board
age-age index - all traits	1.00	1.00	0.31	0.31	0.16	0.08	0.64
simple index - all traits		1.00	0.37	0.37	0.20	0.11	0.69
age-age index			1.00	1.00	0.44	0.16	0.66
simple index				1.00	0.50	0.21	0.69
STBA multi-pulpose					1.00	0.95	0.81
STBA high growth						1.00	0.65
age-age index - all traits							1.00

The extremely poor correlations between either current STBA objectives and the optimum index for the currently defined production system (0.16 and 0.08 for the multi-purpose and high growth objectives, respectively) is a matter of some interest. The objective as described here places a particularly high value on basic density, the cause of these poor relationships. If selections are currently based on, for example, the STBA high growth objective, only 8% of the possible gain in overall enterprise profitability will be made as could have been made if the optimum age-age-inclusive index for all four traits was used.

The genetic correlation between the index calculated in respect of selection trait age-age correlations and the "simple index" is 1.00, suggesting that it is unnecessary to use the more complex method of index derivation involving differential age-age correlations (Equation 10.7), and that the simpler method of using an aggregate economic weight (Equation 10.3) will result in the same individuals being selected.

It is noteworthy that the optimum "age-age selection index" is moderately correlated with that of a production enterprise aimed at producing sawn timber and liner-board derived by Greaves (1999). The value placed on basic density in the enterprise derived by Greaves (1999), however, is around half that as in the currently defined enterprise model.

10.3.3 Expected change in objective traits for each selection index

The expected changes in each objective trait with a 1:100 selection pressure (equating to i = 2.665) applied via each selection index (following Equation 10.11) are presented in Table 10.10.

Table 10.10- Expected change in each objective trait (following Equation 10.11) as a result of a 1:100 selection pressure applied via each selection index.

objective trait	age-age index - all traits	simple index - all traits	age-age index	simple index	STBA multi-pulpose	STBA high growth	age-age index - all traits (Greaves 1999)
improvement objective	max profit flitch/TMP newsprint	max profit flitch/TMP newsprint	max profit flitch/TMP newsprint	max profit flitch/TMP newsprint	equivalent gain in all traits	max growth no loss in branch/stem	max profit sawn-timber/liner-board
MAI	0.0%	0.1%	-4.2%	-3.3%	12.4%	15.6%	5.0%
bark percentage	0.6%	0.6%	-1.4%	-1.2%	2.7%	3.5%	1.5%
branch index	-7.9%	-9.2%	-24.7%	-25.0%	-15.1%	-6.3%	-20.9%
stem sweep	-15.0%	-16.6%	-30.9%	-31.4%	-24.7%	-16.5%	-28.7%
stem taper	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
density	12.0%	11.9%	2.5%	2.4%	-1.0%	-2.0%	6.8%
basic work.str.	10.3%	10.1%	1.0%	0.8%	-2.0%	-2.5%	4.9%
length	5.1%	5.1%	0.5%	0.4%	-1.0%	-1.3%	2.4%
coarseness	-2.1%	-2.1%	0.0%	0.0%	0.0%	0.0%	-1.2%
wood brightness	-2.4%	-2.4%	0.0%	0.0%	0.0%	0.0%	-1.3%

It is noteworthy that the two derived selection indices which contain all traits ("age-age index – all traits" and "simple index – all traits") result in negligible increases in Growth (0%), but large increases in Density (12%) and Basic Working Strength (10%), whilst improving Branch Index (-9%) and Sweep (-16%). The STBA indices, however, provide large increases in Growth (12 and 16%), similar improvements in Branch Index and Sweep, but very small changes in Density (1 and 2%). The derived indices which did not include basic density ("age-age index" and "simple index") result in decreases in Growth. In this situation, the index suggests that slower growing trees be selected in the field, as a means of indirectly capturing trees of higher density.

10.4 Conclusion

Selection indices were derived for selection traits dbh, branch score, stem score, and density based upon a breeding objective of maximising the profitability of an enterprise which grows unpruned radiata pine, harvests, transports, and processes to structural flitch and newsprint from thermo-mechanical pulp. These indices provide negligible increases in Growth which is in contrast to existing STBA "multi-purpose" and "maximum growth indices", but provide much greater improvements in density (Basic Density), Basic Working Stress and Tracheid Length. Improvements in branch size (Branch Index) and stem form (Stem Sweep) did not impact greatly on the production enterprise, but were roughly similar between indices derived in the present work and the STBA indices.

The derived indices are only poorly correlated with the current STBA indices, and indeed, if using the STBA "maximum growth index", only 8% of the potential gain will be achieved, compared with using the optimum index defined here. This is primarily due to the high value placed on density in the currently defined enterprise model. Nevertheless, the derived indices do provide a rational methodology for selecting the best genotypes at a selection age of 10 years for either breeding or deployment.

10.5 Appendices

10.5.1 Appendix: CV selection traits

trait	sources of information	*assumed* CV_G
dbh	• 6%: dbh, *P. radiata* age 10 (Greaves *et al.* 1987) • 7.8%: dbh, *P. radiata* age 10 (White *et al.* 1992b)	7%
branch score	• 14%: branch quality (1-6 score), *P. radiata* age 10 (White *et al.* 1992b) • 20%: branch score (1-6 score), *P. radiata* age 10 (Greaves *et al.* 1987)	14%
stem score	• 14%: straightness score (1-6 score), *P. radiata* age 10 (White *et al.* 1992b) • 14%: stem score (1-6 score), *P. radiata* age 10 (Greaves *et al.* 1987)	14%
density	• 4%: density, *P. radiata* age 5 (Greaves *et al.* 1987) • 4%: density *P. radiata* age 23 (Nyakuengama *et al.* 1999)	4%

10.5.2 Appendix: Correlation between selection traits

	branch score	stem score	density
dbh	• **-0.13** (se 0.07): dbh - branch score *P. radiata* age 10 (Greaves *et al.* 1997) • **0.21**: dbh - branch quality *P. radiata* age 8 (Burdon *et al.* 1992) • **-0.24** (se 0.30): dbh - branch score *P. radiata* age 6 (Dean *et al.* 1983) • **-0.28** (se 0.21): dbh - branch score *P. radiata* age 8 (Cotterill and Zed 1980) • **0.09**: after STBA EBVs for *P. radiata* traits at age 10 years • **assumed value -0.1**	• **0.36**: dbh - straightness score *P. radiata* age 8 (Burdon *et al.* 1992) • **-0.04** (se 0.08): dbh - straightness score *P. radiata* age 10 (Greaves *et al.* 1997) • **0.35** (se 0.03): dbh - stem straightness *P. radiata* age 6 (Dean *et al.* 1983) • **0.11** (se 0.20): stem straightness - branch score *P. radiata* age 8 (Cotterill and Zed 1980) • **0.27**: after STBA EBVs for *P. radiata* traits at age 10 years • **assumed value 0.3**	• **0**: dbh10 - density5 *P. radiata* age 10 (Greaves *et al.* 1997) • **-0.45** (se 0.30): dbh - density *P. radiata* age 6 (Dean *et al.* 1983) • **-0.30**: after STBA EBVs for *P. radiata* traits at age 10 years • **assumed value -0.3**
branch score	•	• **0.64** (se 0.61): branch quality - straightness score *P. radiata* age 8 (Burdon *et al.* 1992) • **0.67** (se 0.04): branch score - straightness score *P. radiata* age 10 (Greaves *et al.* 1997) • **0.59** (se 0.23): branch quality - straightness score *P. radiata* age 6 (Dean *et al.* 1983) • **0.48** (se 0.20): dbh - branch score *P. radiata* age 8 (Cotterill and Zed 1980) • **0.43**: after STBA EBVs for *P. radiata* traits at age 10 years • **assumed value 0.5**	• **0.12** (se 0.02): branch score age 10 - density age 5 *P. radiata* (Greaves *et al.* 1997) • **0.01** (se 0.24): branch quality - density *P. radiata* age 6 (Dean *et al.* 1983) • **-0.02**: after STBA EBVs for *P. radiata* traits at age 10 years • **assumed value 0.1**
stem score	•	•	• **0.10** (se 0.05): straightness score age 10 - density age 5 *P. radiata* (Greaves *et al.* 1997) • **-0.03** (se 0.41): stem score - density *P. radiata* age 6 (Dean *et al.* 1983) • **-0.15**: after STBA EBVs for *P. radiata* traits at age 10 years • **assumed value -0.1**

10.5.3 Appendix: LAR coeffients used in the estimation of age-age correlation

trait	sources of information	*assumed coefficient of LAR*
dbh	• Coefficient of LAR for age-age genetic correlations for **dbh** in *Pinus radiata* estimated from correlations presented by King and Burdon (1991) to be **0.26** • Unpulished results for age-age correlations for **volume** for radiata pine grown in Chile give a coefficient of LAR of **0.26**. • Coefficient of LAR for age-age genetic correlations for **height** in *P. teada* estimated to be **0.08** (Gwaze *et al.*1997). • Coefficient of LAR for age-age genetic correlations for **height** in *Pinus radiata* estimated to be (**0.18 to 0.44**) (Burdon *et al.* 1992, page 221) • Coefficient of LAR for age-age genetic correlations for **height** in Jack pine (*P. banksiana*) estimated to be 0.18 (Riemenschneider 1988) • Coefficient of LAR for age-age genetic correlations for **height** in loblolly pine (*P. taeda*) estimated to be 0.254 (McKeand 1988) • Coefficient of LAR for age-age phenotypics correlations for **height** in *Pinus* species estimated to be 0.31 (Lambeth 1980)	0.25
branch score	• No age-age correlations for branch score.	0.25
stem score	• Unpulished results for age-age correlations for a 3-point stem-form score for radiata pine grown in Chile give a coefficient of LAR of **0.24**.	0.25
density	• Douglas fir: age-age correlation for whole-core density from age-7 to age-15 years approximately 0.91 (interpreted from Figure 3, Vargas-Hernandez and Adams 1992) equating to a coefficient of LAR of **0.16**. • Radiata pine: age-age correlations for whole-core density from age-10 to age-25 years equating to a coefficient of LAR of **0.043** (unpublished data). • Eucalyptus nitens: age-age correlations for whole-core density from age-3 to age-7 years equating to a coefficient of LAR of **0.066** (Greaves et al. 1997). • ***Coefficient of LAR for core density as a selection trait assumed to be 0.05***	0.05

10.5.4 Appendix: Correlations: selection-objective

	dbh	branch score	stem score	density
MAI	• **0.99**: dbh - volume *P. radiata* age 6 (Dean *et al.* 1983) • **Assumed 1.0**	• (see Appendix 10.5.2 – corr. b/n branch score and dbh) • **Assumed -0.1**	• (see Appendix 10.5.2 – corr. b/n stem score and dbh) • **Assumed 0.2**	• (see Appendix 10.5.2 – corr. b/n density and dbh) • **Assumed -0.2**
BIX	• (see Appendix 10.5.2 – corr. b/n branch score and dbh) • **Assumed 0.1**	• **Assumed -1.0**	• (see Appendix 10.5.2 – corr. b/n stem score and branch score) • **Assumed -0.6**	• (see Appendix 10.5.2 – corr. b/n branch score and density) • **Assumed -0.1**
SWE	• (see Appendix 10.5.2 – corr. b/n stem score and dbh) • **Assumed -0.2**	• (see Appendix 10.5.2 – correl. b/n stem score and branch score) • **Assumed -0.6**	• **Assumed -1.0**	• (see Appendix 10.5.2 – corr. b/n stem score and density) • **Assumed -0.1**
TAP	• No information • **Assumed 0**	• No information • **Assumed 0**	• No information • **Assumed 0**	• No information • **Assumed 0**
DEN	• (see Appendix 10.5.2 – corr. b/n density and dbh) • **Assumed -0.2**	• (see Appendix 10.5.2 – corr. b/n branch score and density) • **Assumed 0.1**	• (see Appendix 10.5.2 – corr. b/n stem score and density) • **Assumed 0.1**	• **Assumed 1.0**
BWS	• No information • Assumed genetic correlation between MAI and BWS is similar to that between MAI and density given that density and BWS are assumed to be highly correlated. • **assumed -0.3**	• No information and no basis for assuming the correlation is anything but zero. Whilst changing branch size will be expected to reduce structural stress-grade, the effect of branch size has been modeled here separately and thus no relationship between the branch-size and BWS is assumed. • **Assumed 0**	• No information • **Assumed 0**	• Matheson *et al.* (1997) PRAD25: MOR - MOE 1.02; MOR - density 0.98; MOE - density 1.04; MOE:- stress-grade 0.92; MOR – stress-grade 0.87; density – stress-grade 0.95. • Shelbourne (1997): "*There is evidence, recently rediscovered, that within 5-ring groups, there is only a very weak relationship between density and stiffness (Orman & Harris unpub. data)*". • **Assumed 0.8**
LEN	• -ve relationship postulated by Megraw (1985) • -0.2 McGranahan (*in prep.*) dbh-length • **assumed –0.1**	• No information and no basis for assuming the correlation is anything but zero. • **Assumed 0**	• No information • **Assumed 0**	• 0.77 Chapter 9 - r_g density-length • 0.20 McGranahan (2000) – rg density-length • **Assumed 0.4**
CRS	• No information • **Assumed 0**	• No information • **Assumed 0**	• No information • **Assumed 0**	• -0.44 Nyakuengama et al. (1999) - rg density-coarseness • -0.18 Chapter 9 - rg density-coarseness • 0 McGranahan (2000) - rg density-coarseness • 0.29 Shelbourne et al. (1997) rg density-coarseness • **Assumed –0.1**
BRG	• No information • **Assumed 0**	• No information • **Assumed 0**	• No information • **Assumed 0**	• -0.30 McGranahan (2000) - rg density-brightness • -0.09 Chapter 9 - rg density-brightness • **Assumed –0.2**

10.5.5 Appendix: Ranked *EBV* list – STBA *EBVs*

The top 50 ortets of the 2,414 STBA *EBV* lists ranked (PI_rank) according to *Profitability Index* (PI_index), a ranking of "1" indicating the top individual. Also depicted are the rankings and calculated index values for the two STBA indices (MP_IND and GR_IND): see Table 10.1. **Ortet identification has not been shown** for reasons of confidentiality and the full list of *EBV*s including ortet identification is provided in the excel spreadsheet "**confidential STBA EBVs with index.xls**".

ORTET	BVDBH	BVBRANCH	BVSTEM	BVDEN	PI_index	PI_rank	MP_IND	MP_rank	GR_IND	GR_rank
AA	4.92	6.37	14.48	7.69	3.77%	**1**	6.30	1742	5.50	1699
BB	2.70	11.60	10.15	6.61	3.09%	**2**	5.51	1902	4.12	1993
COC	2.09	3.94	20.01	5.34	2.96%	**3**	4.49	2075	3.07	2151
DON	4.49	10.90	25.62	3.91	2.76%	**4**	8.26	1232	6.17	1503
EE	8.24	22.50	25.68	3.41	2.75%	**5**	13.35	247	10.75	447
FUFF	13.29	9.01	12.90	4.17	2.72%	**6**	12.30	391	12.74	185
GOG	4.03	22.17	30.01	3.33	2.71%	**7**	10.95	643	7.38	1185
HIM	3.38	-5.85	9.39	5.62	2.68%	**8**	2.00	2309	2.48	2213
ITCH	3.27	11.51	19.42	4.49	2.68%	**9**	6.90	1582	4.97	1824
JJ	2.02	-0.09	23.77	4.03	2.60%	**10**	3.97	2136	2.66	2192
KILO	2.58	26.60	27.31	2.99	2.42%	**11**	10.66	698	6.61	1376
LIMA	4.54	0.59	15.02	4.15	2.40%	**12**	4.83	2022	4.48	1926
MAD	1.82	24.09	15.82	4.18	2.37%	**13**	8.32	1224	5.19	1774
NILE	8.05	20.74	21.22	2.82	2.33%	**14**	12.33	380	10.19	547
OPPO	9.28	10.57	12.50	3.63	2.32%	**15**	9.92	875	9.58	677
PLOP	4.59	18.80	28.89	2.27	2.27%	**16**	10.45	766	7.38	1187
QUE	10.52	8.77	20.38	2.52	2.26%	**17**	11.23	600	10.71	454
ROAR	3.72	14.23	15.34	3.75	2.25%	**18**	7.35	1470	5.52	1696
SUS	-1.77	13.03	9.21	5	2.25%	**19**	2.74	2263	0.54	2324
TJT	6.41	7.27	11.10	3.85	2.22%	**20**	7.12	1518	6.71	1347
UMM	7.32	10.34	20.39	2.75	2.22%	**21**	9.44	980	8.24	980
VIV	4.41	9.76	17.17	3.38	2.20%	**22**	7.02	1547	5.61	1667
WOW	10.73	14.31	30.73	1.22	2.20%	**23**	13.75	212	12.01	250
XX	10.72	11.97	7.47	3.52	2.14%	**24**	10.64	710	10.74	451
YY	4.45	12.26	15.63	3.31	2.12%	**25**	7.43	1446	5.89	1588
ZOO	5.35	18.97	24.05	2.1	2.05%	**26**	10.45	764	7.83	1082
ABE	8.40	18.21	18.25	2.36	2.04%	**27**	11.67	513	10.04	586
ACE	11.03	13.34	19.69	1.88	2.02%	**28**	12.51	359	11.68	302
ADON	6.37	30.07	20.96	2.13	2.00%	**29**	13.26	255	9.94	607
AE1	11.81	16.84	14.94	2.15	1.97%	**30**	13.28	252	12.57	195
AFTA	8.72	14.74	1.18	3.86	1.93%	**31**	9.22	1031	9.16	786
AGE	13.23	11.99	20.64	1.31	1.93%	**32**	13.78	205	13.38	121
AHHH	10.97	0.59	13.18	2.34	1.91%	**33**	8.91	1093	9.76	642
AI	4.71	15.71	23.36	1.87	1.90%	**34**	9.23	1028	6.86	1318
AJ	7.63	9.79	16.29	2.31	1.89%	**35**	9.07	1065	8.26	978
AK47	8.51	33.48	27.10	0.96	1.89%	**36**	16.12	42	12.41	207
AL	12.51	0.80	26.99	0.67	1.89%	**37**	11.52	542	11.65	306
AE2	11.21	15.38	13.15	2.15	1.87%	**38**	12.35	375	11.81	275
AMMA	7.63	14.78	29.28	0.85	1.87%	**39**	11.62	528	9.43	708
ANN	6.34	7.53	25.19	1.45	1.86%	**40**	8.70	1125	7.27	1215
AWOL	11.85	24.17	28.44	0.41	1.86%	**41**	16.43	31	14.08	81
APE	10.95	8.90	21.96	1.21	1.84%	**42**	11.72	504	11.15	385
AE3	10.59	17.41	12.81	2.15	1.83%	**43**	12.35	376	11.54	330
AQUA	10.78	17.80	12.29	2.15	1.82%	**44**	12.51	358	11.72	294
ARC	3.96	9.59	24.64	1.61	1.81%	**45**	7.51	1428	5.53	1693
ASS	11.98	21.34	17.92	1.32	1.79%	**46**	14.72	118	13.40	119
ATE	7.96	15.43	16.70	1.86	1.76%	**47**	10.59	743	9.26	766
AU	10.44	14.46	17.91	1.43	1.75%	**48**	12.16	415	11.25	362
AVE	7.41	0.67	15.64	2.07	1.75%	**49**	6.83	1599	6.91	1306
AWE	7.70	5.24	28.50	0.64	1.74%	**50**	9.46	975	8.26	979

Chapter 11

Estimation of genetic gain from multi-trait selection for an objective which maximises the profitability of a vertically integrated enterprise producing timber flitch and newsprint

Chapter 11 is currently being prepared for submission:
Chambers P.G.S and Greaves B.L. (1999): Estimation of genetic gain from multi-trait selection for an objective which maximises the profitability of a vertically integrated enterprise producing timber flitch and newsprint. *For. Sci.*

11.1 Introduction

The conventional approach to selection of breeding stock is to define an objective and then use knowledge of genetic and phenotypic covariances to define a set of selection criterion (Goddard 1998). Hence the choice of selection criteria will be influenced by which traits are part of the breeding objective (Woolaston and Jarvis 1995), but the reverse should be avoided as it may lead to the omission of economically important traits (James 1987). In the strict application of this approach, covariances have no place in the definition of the objective (Goddard 1998). Therefore, the traits in the profit function (breeding objective traits) should relate as directly as possible to the sources of income and cost, and the profit

function should be as close as possible to true profit. Decisions regarding which traits to include in the profit function should ideally be based on economic grounds alone (Woolaston and Jarvis 1995). Traits should not be excluded on the basis of a lack of information (James 1982) or on the fact that they may be difficult to measure (Woolaston and Jarvis 1995). Harris (1970) suggests that the decision of which traits to include in the objective depend on the additional amount of economic improvement that can be made relative to the 'cost' of making that improvement.

The value of a breeding objective trait to breeding was investigated in Chapter 8, by comparing the impact on overall enterprise profitability of a 10% increase in each trait. However, this methodology assumes that a 10% change in one breeding objective trait is independent of changes in another. Indeed, the importance of each trait in the breeding objective is a function, not only of the economic weights derived from a profit function, but the exploitable variation for each trait and the correlations with other traits in the objective. Further, selections are normally made at a much earlier age on a number of criteria used to predict the breeding values of each trait in the breeding objective at a later age. This adds another level of complexity (a component of age-age correlation) for tree breeders endeavoring to answer such issues as how to maximise economic gain and what trees to choose at selection age to achieve this. To summarise, the economic importance of each breeding objective trait can be gauged only after considering the following issues:

- genetic variation for each selection criteria;
- genetic relationship between selection criteria;
- age-age correlations for selection criteria between selection age and the ages when economic advantage is realised;
- genetic relationship between selection traits and economic objective traits; and
- genetic variation within each economic objective trait.

The current chapter attempts to define which combination of breeding objective traits are the 'best' traits in terms of maximising economic gain for a tree breeder seeking to select a deployment population at age 10. It also examines a scenario, where a budgetary constraint is placed on the amount of money available to carry out assessments of these selection criteria. An optimum selection strategy is devised by simulation, given a budgetary constraint of $100,000.

11.2 Methods

11.2.1 Selection Criteria

Selection criteria were assumed to be assessed at age 10 and were defined as follows:

- diameter growth (dbh) – measured at breast height (1.3m) over bark (cm);
- branch quality score (branch) – a normally distributed, subjective form score (1-6), combining branch angle and thickness, where 1 represents thick, steep angled branches and 6 represents thin, flat angled branches (Cotterill and Dean 1990);
- stem straightness (stem) - a normally distributed, subjective form score (1-6), where 1 is crooked and 6 is straight (Cotterill and Dean 1990);
- basic density (density) – the oven-dry weight of wood per unit of green volume;
- tracheid length (length) – the mean length of wood tracheids, expressed in millimetres (as measured on a Kajaani Fibre-Analyser);
- tracheid coarseness (coarse) – the mass of the cell wall per unit length of cell (mg/m); and
- wood brightness (bright) – a function of the light scattering and light absorption properties of ground wood samples measured at a wavelength of 457nm and expressed as a percentage of the reflectance.

The assumed genetic parameters for the selection criteria (following Chapter 10) are listed in Table 11.1.

Table 11.1- Assumed genetic parameters for the selection criteria at age 10: CV_g and CV_P are measures of the genetic and phenotypic coefficients of variation respectively and h^2 is the narrow sense heritability for each selection trait. Also depicted are the assumed genetic correlations between the selection traits at assessment age.

Selection Trait	CV_g	CV_p	h^2	r_g					
				branch	stem	density	length	coarse	bright
dbh	7.0%	16.0%	0.2	-0.10	0.30	-0.30	-0.10	0.00	0.00
branch	14.0%	20.0%	0.3		0.50	0.10	0.00	0.00	0.00
stem	14.0%	31.0%	0.2			-0.10	0.00	0.00	0.00
density	4.0%	6.0%	0.5				0.30	-0.20	-0.20
length	5.0%	9.0%	0.3					0.70	0.30
coarse	5.0%	8.0%	0.4						-0.20
bright	4.5%	6.0%	0.3						-

Phenotypic correlations (r_p) between selection criteria x and y were calculated from the genetic correlations (r_g) and heritability estimates presented in Table 11.1, after:

$$r_{p(x/y)} = r_{g(x/y)}\sqrt{h_x^2 . h_y^2} \qquad (11.1)$$

where:

- h_x^2 and h_y^2 are the assumed heritability estimates for selection traits x and y respectively.

This methodology assumes that the environmental covariance is zero. Phenotypic correlations between selection criteria were required to examine multi-trait selection options (see Section 11.2.5 below).

11.2.2 Economic Objective

The definition of an economic breeding objective for any industrial enterprise first requires that an adequate model of the production system for that enterprise exist (Ponzoni and Newman 1989). The production enterprise assumed here was defined as a closed system, where all merchantable wood that was grown was processed within the enterprise and sold as timber flitch and high brightness newsprint grade paper (Chapter 7). All sections of the enterprise were treated as if they were components of a single business, hence no transfer prices are paid for the movement of wood within the production system. Costs were incurred in growing, harvesting, transport, chipping/sawing, pulping and paper (newsprint) production,

whilst income to the enterprise was received from the sale of timber flitch (to a near-by sawmill) and newsprint (Chapter 7).

As incomes and costs occur at different times in the production system, present value analysis was employed to accommodate differences in the timing of costs and returns. A discount rate of 5% was assumed. The economic methodology used to describe the production system was *Profitability Index* (Chapter 7). *Profitability Index* is essentially the ratio of the present value of profit (P_{PV}) (being total present value income minus total present value costs) and the present value of total costs (Anthony and Reece 1989) and estimated following:

$$PI = 100.\frac{(I_{PV} - C_{PV})}{C_{PV}} \qquad (11.2)$$

where:

- I_{PV} and C_{PV} are expressions of present value income and costs respectively; and
- PI is the *Profitability Index*.

"Present" was defined as the time of clearfall harvest (at rotation end, 25 years), and all costs and incomes were appreciated to the time of clearfall using the general formula:

$$PV = V\left(1+\frac{d}{100}\right)^{(t_{CF}-t_V)} \qquad (11.3)$$

where:

- PV is the value at the time of clearfall harvest (t_{CF}) at rotation end of a cost or income V, occurring prior to rotation end (at time t_V), and d is the discount rate.

Income was derived from the sale of timber flitch and newsprint on three occasions throughout the plantation lifespan (Chapter 7), being at each of the two thinning operations (T1 and T2 respectively) and at clearfall (CF). Hence present value of income was calculated as:

$$I_{PV} = \sum_{y=T1,T2,CF}\left[\left(IFL_Y + INEWS_Y\right)\left(1+\frac{d}{100}\right)^{(t_{CF}-t_y)}\right] \qquad (11.4)$$

where:

- IFL_y and $INEWS_y$ are the incomes derived from sale of timber flitches and newsprint respectively by harvesting operation (y); and

- t_y is the age of harvest operations *T1*, *T2* and *CF* in relation to the time of establishment being year zero.

Similarly, the present value of total costs was derived following:

$$C_{PV} = CGROW_y + \sum_{y=T1,T2,CF}\left[CPROD_y\left(1+\frac{d}{100}\right)^{(t_{CF}-t_y)}\right] \qquad (11.5)$$

where:

- $CGROW_y$ is the total growing cost per hectare of plantation at the time of clearfall; and

- $CPROD_y$ is the per-hectare sum of all costs associated with the production of timber flitches and newsprint from standing forest by harvesting operation y. This includes harvesting, transport, debarking, chipping, sawing, pulping and newsprint production costs (Chapter 7).

11.2.3 Breeding Objective Traits

The breeding objective traits were defined as the traits which a forest grower seeks to optimise due to their more direct impact on production system profitability (Woolaston and Jarvis 1995). The choice of breeding objective traits used in the present work (see Chapter 8) was the outcome of much deliberation with the key considerations being:

- complete coverage of all aspects of the production system defined in Chapter 7;

- historical perceived performance;

- performance as indicated by previous work in this field (see Chapters 4 and 5); and

- availability of data for construction of necessary relationships.

Ten traits (Table 11.2), selected as having an influence on the costs and incomes of the current production enterprise, were evaluated in the current work: mean annual increment (*MAI*), bark percentage (*BRK*), branch index (*BIX*), stem sweep (*SWE*), stem taper (*TAP*), basic density (*DEN*), basic working stress of timber (*BWS*), mean tracheid length (*LEN*), mean tracheid coarseness (*CRS*), and mean wood brightness (*BRG*). The impact that each of these traits exert on enterprise profitability is detailed in Chapter 8. Genetic parameters for each breeding objective trait are given in Table 11.2 and were based on the assumed values used

in Chapter 10. Economic weights (W_{PI}) for each of the breeding objective traits identified are also presented in Table 11.2. These values represent the change in *Profitability Index* due to a unit increase in each breeding objective trait, when all other traits are held constant. Economic weights were derived in Chapter 8.

Table 11.2- Breeding objective traits: assumed means, genetic coefficients of variation (CV_g) and narrow sense heritability (h^2) after Chapter 10 and estimated economic weights (defined as the absolute change in overall enterprise *Profitability Index*, in percentage points associated with a unit change in a trait) after Chapter 8.

Breeding Obj. Trait	units	mean	CV_g	h^2	W_{PI}
MAI	m^3/ha/yr	20	7.0%	0.20	0.33%
BRK	%	8	4.0%	0.35	-0.09%
BIX	cm	5	14.0%	0.30	-0.85%
SWE	mm/m	3	14.0%	0.25	-0.14%
TAP	mm/m	5	4.0%	0.25	-0.14%
DEN	kg/m^3	400	4.0%	0.50	0.08%
BWS	MPa	6.5	4.0%	0.40	0.76%
LEN	mm	2.5	5.0%	0.35	5.87%
CRS	mg/m	0.5	5.0%	0.50	-2.05%
BRG	%	50	4.5%	0.30	0.32%

11.2.4 Correlations between Selection Criteria and Objective Traits

The assumed values for the genetic correlations between selection criteria (as assessed at age 10) and breeding objective traits (assuming a rotation age of 25 years) are given in Table 11.3. These correlations were based on the values designated in Chapter 10 and represent, where possible, the average value of a number of commonly reported estimates in the literature. However, many of the genetic parameters assumed (Appendix 10.5.1 to Appendix 10.5.4, Chapter 10) were based on unverified assumption (i.e. there is little scientific evidence currently available to support the assumed value).

Table 11.3- Assumed genetic correlations between selection criteria (shown in lower case) and breeding objective traits (shown in upper case), after Chapter 10.

Selection Trait	Breeding Objective Trait									
	MAI	BRK	BIX	SWE	TAP	DEN	BWS	LEN	CRS	BRG
dbh	0.90	0.35	0.10	-0.20	0	-0.20	-0.20	-0.10	0	0
branch	-0.10	0	-0.90	-0.60	0	0.10	0	0	0	0
stem	0.20	0	-0.60	-0.90	0	0.10	0	0	0	0
density	-0.20	0	-0.10	-0.10	0	0.90	0.80	0.30	-0.20	-0.20
length	-0.10	0	0	0	0	0.30	0	0.90	0	0.30
coarse	0	0	0	0	0	-0.20	0	0	0.90	-0.20
bright	0	0	0	0	0	-0.20	0	0.30	-0.20	0.90

11.2.5 Selection Index and Gain from Selection

From Hazel's (1943) definition of aggregate genotype, the breeding objective function may be defined as a linear combination of the derived economic weights given in Table 11.2 and the breeding values of each objective trait:

$$H_{PI} = 0.33A_{MAI} - 0.09A_{BRK} - 0.85A_{BIX} - 0.14A_{SWE} - 0.14A_{TAP} + 0.08A_{DEN} + 0.76A_{BWS} + 5.87A_{LEN} - 2.05A_{CRS} + 0.32A_{BRG} \quad (11.6)$$

where:

- H_{PI} is the aggregate genotypic breeding value for profitability index; and
- A_x are the breeding values for each objective trait, x.

In order to predict the value of H_{PI} (at a rotation age of 25 years), selections were based on multiple criteria assessed at 10 years. The selection strategies considered here refer to forward selection combining individual and (or) family information for each selection criteria and assumed to be based on an initial sample size of 30 individuals from a half-sib family. Indeed, Cotterill and James (1984) have demonstrated that a sample size of 30 progeny per family can provide a reliable estimate of the family mean. The coefficient of relationship among half-sibs was assumed to be 0.25 following Falconer and Mackay 1996.

Selection index coefficients were derived from the assumed economic weights and genetic parameters following:

$$\mathbf{b} = \mathbf{P}^{-1}\mathbf{A}\mathbf{w} \quad (11.7)$$

where:

where:

- **b** is a vector of selection index coefficients for the selection traits;
- **P** is a phenotypic covariance matrix between selection criteria;
- **A** is a genetic covariance matrix between traits in the breeding objective and the selection criteria; and
- **w** is a vector of the economic weights, expressed for each objective trait.

The covariance elements of **P** and **A** were derived from:

$$\mathrm{cov}_{pq} = r_{(p/q)}\sigma_p\sigma_q \qquad (11.8)$$

where:

- $r_{(p/q)}$ is the genetic or phenotypic correlation between elements p and q; and
- σ_p and σ_q are the standard deviations of elements p and q respectively.

The construction of the **P** and **A** matrices combining individual and (or) family level information for each selection criteria followed the procedure outlined in White and Hodge (1989), Chapter 10.

Economic gain (G) towards the breeding objective from selections based on each multi-trait selection index were estimated from:

$$G = i\sigma_I \qquad (11.9)$$

where:

- i is the selection intensity; and
- σ_I is the standard deviation of the selection index, estimated as (after White and Hodge 1989):

$$\sigma_I = \sqrt{\mathbf{b'Pb}} \qquad (11.10)$$

The expected change in the breeding objective traits (o) due to selection on a multi-trait index was estimated after (White and Hodge 1989):

$$o = i\frac{\mathbf{A'b}}{\sqrt{\mathbf{b'Pb}}} \qquad (11.11)$$

11.2.6 Efficiency of Selection

The relative efficiency, in terms of gains in the breeding objective (i.e. enterprise profitability), of selecting on a given index versus an index combining individual and family information for all traits (i.e. an "optimum" index), was calculated as:

$$E = \frac{\Delta G_{index}}{\Delta G_{optimum}} \qquad (11.12)$$

where:

- ΔG_{index} is the gain in profitability for a given selection index; and
- $\Delta G_{optimum}$ is the gain in profitability when selections are based on an index combining individual and family information for all selection criteria.

11.2.7 Sensitivity Analysis

To explore the sensitivity of the derived selection indices to variation in the assumed input parameters, Monte-Carlo simulation was used to generate 10,000 sets of genetic parameters using @RISK software (Palisade 1997). This was critical, given the uncertainty of a number of the assumed values for unverified genetic parameter estimates (Section 11.2.4). All input parameters were allowed to vary with an assumed uniform probability distribution with bounds as:

- genetic coefficient of variation: assumed value ±50%;
- genetic correlations: assumed value ±0.2; and
- economic weights: assumed value ±50%

11.2.8 Assessment Cost Deployment Scenario

It is realistic to assume that assessments can not be made on every tree for every trait due to budgetary constraints. This is especially the case for the more expensive to assess wood properties. The questions of which traits a breeder should assess to maximise gain, and how many individuals per family should be assessed for these traits are important given a limited budget.

10,000 assessment strategies were randomly generated by Monte-Carlo simulation with the following constraints:

- the enterprise was assumed to have an annual deployment program of 3000ha;
- the present value of total costs for processing a hectare of forest into structural-grade flitch and newsprint was $326,948 (after Chapter 7);
- the maximum budget for assessment was $100,000;
- the total number of families from which to choose a deployment population was either: (a) 20, (b) 50, (c) 80, or (d) 100;
- the number of individuals assessed in each family for each trait was either: (a) 5, (b) 10, (c) 25, or (d) 50; and
- assessments of growth and form traits (i.e. dbh, branch and stem) are assumed to be made for every simulated strategy.

The assumed assessment costs of selection by trait are presented in Table 11.4.

Table 11.4- Cost of assessing each selection trait at age 10, as a function of sampling cost, processing cost, the number of families assessed (*n*) and the number of trees assessed per family (*t*).

Trait	Sampling cost (per tree)	Processing cost (per tree)	Sampling cost (total)	Processing cost (total)
dbh	$1	$0	$1 x *n* x *t*	$0
branch	$2	$0	$2 x *n* x *t*	$0
stem	$2	$0	$2 x *n* x *t*	$0
density	$25*	$30**	$25 x *n* x	$30 x *n* x
coarse			$\max(t_{den},t_{crs},t_{len})$***	$\max(t_{den},t_{crs})$
length		$50		$50 x *n* x *t*
bright	$25	$10	$25 x *n* x *t*	$10 x *n* x *t*

* only one cost of $25 is incurred if density, length and coarse are sampled as it is assumed that all of these may be measured on the one core sample.
** only one cost of $30 is incurred if density and coarse are measured by the SilviScan apparatus, which provides an estimate of both traits per run.
*** the "wood core" sampling cost is dependant on the greatest number of trees per family assessed for either density, coarse or length.

It is assumed that assessments of basic density and tracheid coarseness are conducted using the SilviScan apparatus (Evans *et al.* 1995) and hence assessments of either of these traits will always provide information on the other at no extra cost. It is also assumed that samples of tracheid length can be made from the same wood core as used by SilviScan, however assessments must be made separately via peracetic acid digestion and Kajaani analysis. A separate core must

be sampled to assess wood brightness with assessments for this selection trait conducted separately also, via spectromic analysis a ground sample.

11.3 Results and Discussion

11.3.1 Gains from Selection

The gain in enterprise profitability from multi-trait selection on a number of different selection indices is shown in Table 11.5.

Table 11.5- Multi-trait selection strategies, where: "c" represents individual-tree (combined) selection and "f" represents selections based on family mean information only (assuming 30 individuals per half-sib family). Blank cells depict that the trait is not used in selection. Gain is expressed in terms of increase in the profitability of the enterprise, expressed as a percentage of total costs. The present value of gain at the time of plantation establishment of the future gain is given following Equation 8.34 (Chapter 8).

Index	dbh	branch	stem	density	length	coarse	bright	Gain in Profitability(%)	Value of Gain ($\$x10^6$)	Efficiency of Selection
1	c							0.05	0.14 M	1%
2	c	c	c					1.20	3.48 M	33%
3	c	c	c	f				2.09	6.05 M	58%
4	c	c	c	c				2.82	8.17 M	78%
5	c	c	c		f			1.84	5.33 M	51%
6	c	c	c			f		1.31	3.79 M	36%
7	c	c	c				f	1.42	4.11 M	40%
8	c	c	c	f		f		2.11	6.11 M	58%
9	c	c	c		f	f	f	2.46	7.13 M	68%
10	c	c	c	f	f	f	f	2.60	7.53 M	72%
11	c	c	c		c			2.24	6.99 M	62%
12	c	c	c			c		1.42	4.11 M	39%
13	c	c	c				c	1.66	4.81 M	46%
14	c	c	c	c		c	c	3.22	9.33 M	89%
15	c	c	c	c	c	c	c	**3.60**	**10.43 M**	**100%**

Table 11.5 shows that combined selection for dbh alone (index 1) only captures 1% of the possible gain from an "optimum" index containing all traits (index 15). Combined selection for growth and form traits (index 2), a commonly employed assessment strategy in Southern Australia increases enterprise profitability by 1.20%, equating to a present value gain of $3.48M dollars, however this strategy

still only captures 33% of the gain captured by index 15 (Table 11.5). Including density in a selection index results in dramatic increases in gain, underlining the importance of this trait for the currently defined enterprise (Chapter 8). There is also a dramatic increase in profitability depending on whether assessments of density are made on individual trees (combined selection) or on family means (family selection): index 3 compared with index 4 (Table 11.5). Indeed a selection strategy adopting individual-tree assessments of dbh, branch, stem and density (index 4) yields 78% of the gain achieved by index 15. Another possibility revealed by Table 11.5 is that there seems little point in including tracheid length, coarseness or brightness in a selection index at the expense of density (compare index 3 with indices 5 to 7). Considering the cost involved with the estimation of these wood traits, it may be prudent to concentrate solely on sampling a core and assessing density and coarse (index 8) with the SilviScan device (Evans *et al.* 1995).

Table 11.6 depicts the change in breeding objective traits due to selection based on a number of indices defined previously in Table 11.5 (above). It would seem that selections based on index 1 (individual-tree assessment of dbh only) will result in a substantial decrease in MAI (-8.6%, assuming a mean of 20 m^3/ha/yr at rotation age – Table 11.2). This is due primarily to the large value placed on density by the current enterprise model. The negative relationship between dbh and density (described in the **P** matrix), and indeed the negative relationship between dbh and DEN, and MAI and density (as defined in the **A** matrix) causes the index to indirectly select against growth, when no information on density is available.

All the selection indices investigated result in positive gains in DEN, except index 13, where the strategy is to increase profitability by selecting for growth, form and bright traits. Needless to say, the largest gain in BRG was predicted when the strategy follows index 13. Changes in LEN were always positive, while changes in BIX always negative, regardless of the selection strategy adopted (Table 11.6).

For most of the more costly selection traits to assess (i.e. density, length and bright), assessments made on family means predicted substantially less economic gain than individual-tree assessments. Figure 11.1 shows this clear distinction in the capture of gain for 10,000 randomly simulated selection strategies based on three main criteria:

- no assessment of density;
- family-mean assessment of density; and'
- individual-tree assessment of density.

Table 11.6- Gain in overall enterprise profitability (expressed as a percentage of total costs) and change in breeding objective traits (expressed as a deviation from the mean of the unselected population- see Table 11.2 for assumed means) for various selection indices (defined in Table 11.5).

Index	Overall Gain	Gain in Breeding Objective Traits									
	in Profitability	MAI	BRK	BIX	SWE	TAP	DEN	BWS	LEN	CRS	BRG
	%	m^3/ha/yr	%	cm	mm/m	mm/m	kg/m^3	MPa	mm	mg/m	%
1	0.05	-1.72	-0.154	-0.095	0.11	0	4.36	0.011	0.017	0	0
2	1.20	-0.04	-0.008	-1.018	-0.56	0	3.21	0.004	0.001	0	0
3	2.09	-0.04	0.017	-0.612	-0.38	0	16.19	0.209	0.037	-0.005	-0.47
4	2.82	-0.23	0.017	-0.507	-0.32	0	25.31	0.247	0.062	-0.089	-0.77
5	1.84	-0.07	0.002	-0.659	-0.37	0	6.09	-0.001	0.098	0.000	0.59
6	1.31	-0.03	-0.008	-0.930	-0.51	0	4.50	0.004	0.001	-0.011	0.22
7	1.42	-0.03	-0.007	-0.858	-0.47	0	0.59	0.003	0.026	-0.003	1.34
8	2.11	-0.04	0.017	-0.545	-0.34	0	13.99	0.207	0.059	-0.008	0.72
9	2.46	-0.09	0.006	-0.490	-0.27	0	10.94	-0.003	0.135	-0.022	1.03
10	2.60	-0.07	0.014	-0.480	-0.29	0	14.01	0.104	0.114	-0.017	0.85
11	2.24	-0.13	0.002	-0.542	-0.30	0	7.83	-0.001	0.148	0.000	0.89
12	1.42	-0.03	-0.007	-0.859	-0.47	0	5.66	0.003	0.001	-0.021	0.41
13	1.66	-0.03	-0.006	-0.734	-0.40	0	-1.80	0.003	0.049	-0.006	2.60
14	3.22	-0.21	0.017	-0.448	-0.29	0	21.41	0.328	0.091	-0.015	1.07
15	3.60	-0.24	0.014	-0.389	-0.24	0	20.84	0.230	0.159	-0.022	1.36

11.3.2 Sensitivity Analysis

The five most critical input parameter values in the prediction of economic gain (increases in *Profitability Index*) for the enterprise currently defined are given in Table 11.7. The most sensitive input parameter was the genetic coefficient of variation for DEN (i.e. the genetic variation of basic density as measured at rotation age – 25 years – a breeding objective trait). Most other input parameters showing a higher degree of sensitivity were genetic correlations between the selection trait density and traits in the breeding objective (Table 11.7). Of the input parameters not shown in Table 11.7, the genetic correlation between density (selection trait) and DEN (breeding objective trait) was the most important. In general, the results of the sensitivity analysis reflected the significance of basic density to the production enterprise as currently defined.

Table 11.7- Sensitivity analysis: five most critical input parameters. Rank order correlation (higher value indicates more critical assumption) and "Δprofitability per Δinput par." indicates the leverage of the input assumption on the estimated enterprise *Profitability Index*.

input parameter	assumed value	rank-order correlation	Δ profitability per Δ input par.
coefficient of variation - DEN	4.0%	0.42	0.9% per 1%
correlation density-LEN	0.30	0.38	0.6% per 0.1
correlation density-BRG	-0.2	0.25	0.5% per 0.1
economic weight - density	0.08%	0.24	0.5% per 1%
correlation length-BIX	0	-0.21	0.4% per 0.1

The sensitivity analysis indicated that many of the less certain input parameters (Section 10.5, Chapter 10) were not dominant inputs – that is, variation in the assumed value did not greatly alter the predicted value of economic gain. One exception was the genetic correlation between length (selection trait) and BIX (breeding objective trait), which the authors had no reason to assume a value other than zero. This correlation should be verified. In addition, another key unverified assumption was that in the construction of the **P** matrix, environmental covariance was assumed to be zero.

11.3.3 Assessment Cost Deployment Scenario

Figure 11.1 depicts the estimates of economic gain (*Profitability Index*) for family based forestry deployment for 10,000 randomly generated cost assessment strategies. Promisingly, selection strategies resulting in high economic gain were generated even at low cost assessment budgets (<$100,000). Further, given the low increase in economic gain beyond around the $100,000 mark (Figure 11.1), there seems little point (given the current scenario assumptions) in spending more than this amount. A clear distinction was shown between selection strategies containing no information on density, and strategies incorporating family mean information on density, and individual-tree information on density (see also Table 11.5). Given the costly nature of individual-tree assessments for density (Table 11.4) it is interesting to note that a number of the 10,000 randomly generated strategies achieve this under the $100,000 budget constraint (Figure 11.1). In most of these random cases density (in conjunction with coarse) was assessed (among other traits) on 10 trees per family from 100 families (data not shown), which corresponds to an assessment cost of $55,000, and economic gain of 2.73%. Comparing this predicted value of gain with those of the various strategies shown in Table 11.5 (which all incorporate individual-tree assessments for growth based on a sample size of 30 trees per family) it shows that if selections were based purely on an

individual-tree assessment of SilviScan density (and coarse) for 10 trees per family (given a total of 100 families), i.e. ignoring tree growth and form, 58% of the economic gain of an 'optimum' index could be attained. A question arises- is it worthwhile carrying out selections for growth?

However, it is very unlikely that any selection system will tend to exclude some assessment of growth rate. Indeed volume is easy to assess and easy to conceptualise, and certainly carries some level of comfort to forest and business managers. Therefore, while the estimated advantage of including dbh in a selection index aimed at increasing overall enterprise profitability is small, it is difficult to imagine the trait being excluded. Further, if assessments are to made on traits such as branch and stem in the forest, the miniscule amount of extra resources required to 'wrap a diameter tape around each tree' would certainly not be an issue.

Figure 11.1- Gain in enterprise profitability (*Profitability Index*) versus cost of assessment. Each data point represents a randomly generated assessment option for a selection index incorporating: (i) no information of density, (ii) selection for density from family means, (iii) individual-tree selection for density (combined selection). Simulations followed the assumptions detailed in Section 11.2.8 in all cases. 10,000 simulations were conducted across all selection strategies.

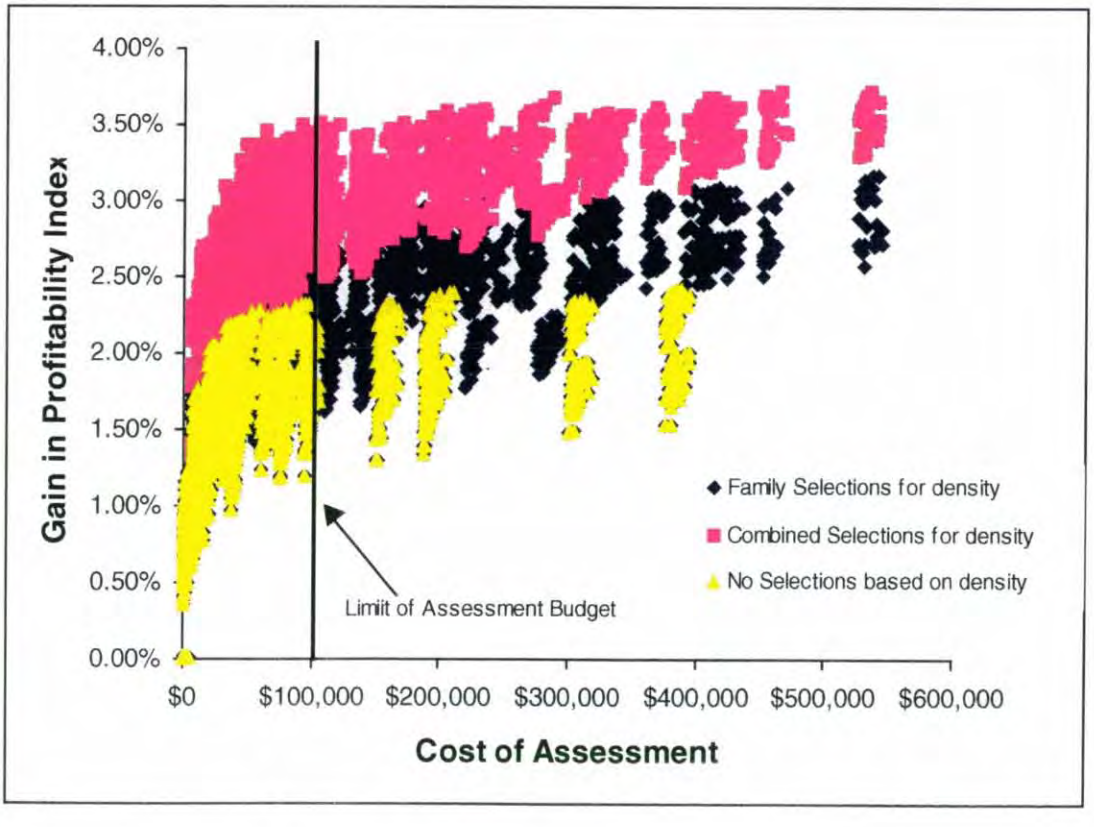


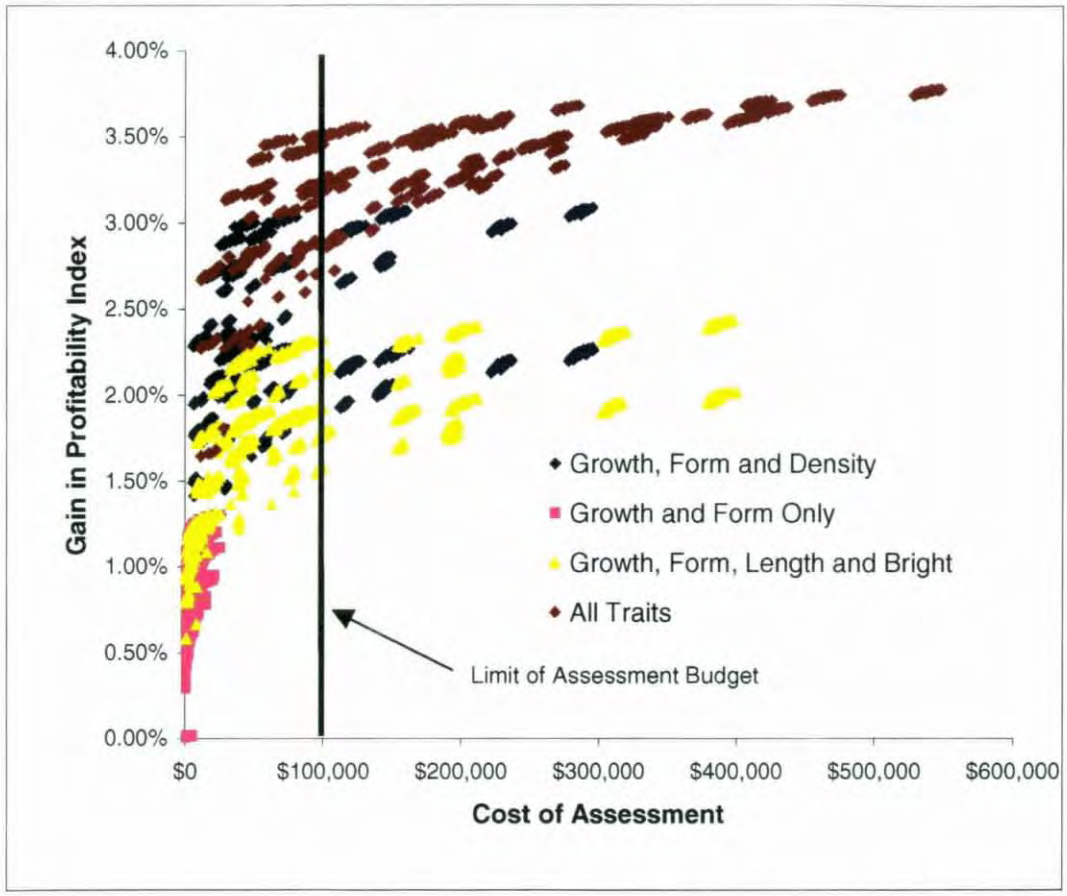
Figure 11.2 examines the impact of the total number of families assessed and the number of trees assessed per family on the predicted economic gain in four major selection strategies:

- a strategy including only growth and form traits (i.e. dbh, branch and stem);
- a strategy combining growth and form traits with length and bright;
- a strategy combining growth and form traits with density (and coarse); and
- a strategy combining all traits.

For each of these strategies, 2000 assessment options were randomly generated allowing the total number of families and the number of trees assessed per family to vary according to the assumptions previously defined in Section 11.2.8.

Selection strategies requiring that some assessment be made on all traits, unsurprisingly resulted in the largest predicted gain (Figure 11.2). However strategies combining growth and form traits with density (especially strategies including individual-tree density assessments) were also shown to predict large economic gain. Indeed, the "two-tiered" effect depicted in Figure 11.1, regarding the differences in predictions of gain from family-mean, compared with individual-tree selections on density is also evident in Figure 11.2 for the two selection strategies including this trait. Strategies combining growth and form traits with length and bright resulted in moderate predictions of economic gain, while strategies including just growth and form traits resulted in low predicted gains compared with the strategy including all traits.

Figure 11.2- Gain in enterprise profitability (*Profitability Index*) versus cost of assessment. Each data point represents a randomly generated assessment option for a selection index incorporating: (i) growth and form traits only (i.e. dbh, stem and branch), (ii) growth, form and SilviScan traits (i.e. dbh, stem, branch, density and coarse), (iii) growth, form, length and bright traits, and (iv) all traits. Simulations followed the assumptions detailed in Section 11.2.8 in all cases. 2000 simulations were generated per selection strategy.



The optimum selection strategy for an assessment budget of $100,000 is detailed in Table 11.8, following 10,000 maximisation simulations. It is assumed that 50 trees will be selected from the total of 5000 (i=2.665). In all cases, it was assumed that dbh, branch, stem were assessed on each tree.

Table 11.8- Optimum selection strategy (within simulation constraints) for the family forestry deployment scenario, assuming a maximum assessment budget of $100,000. Selection strategy "c" indicates a strategy based on individual-tree (i.e. combined) selections. *PI* represents the *Profitability Index*. Increase in PV gain represents the increase in enterprise profit of the deployment population, at the plantation establishment of that population.

Selection Criterion	No. Families (total)	No. Trees Assessed per Family	Selection Strategy	Assessment Cost	Increase in *PI*	Increase in PV Gain
dbh	↑	50	c	$5,000	0.02	0.6 M
branch	↑	50	c	$10,000	1.09	3.2 M
stem	↑	25	c	$5,000	0.18	0.5 M
density	100	10	c	$55,000	1.69	4.9 M
length	↓	5	c	$25,000	0.36	1.1 M
coarse	↓	10	c	-	0.16	0.5 M
bright	↓	-	none	-	-	-
Total Assess. Cost				$100,000		
Economic Gain					3.51%	10.8 M

Table 11.8 shows that selections based on dbh result in very little increase in economic gain ($0.6 million dollars at a present value of plantation establishment). However, compared with the cost of assessing this trait ($5000), this cost appears to be well justified. Indeed, the assessment costs for any of the selection criteria included in the 'optimum' strategy (Table 11.8) were well justified compared with the economic gain predicted. A strategy combining individual-tree selection for all traits (index 15 – Table 11.5) would cost $435,000 to assess (assuming 30 trees per family were assessed for each selection trait) – a cost much less than the *Present-Value* of gain predicted ($10.4M).

Of major importance in determining the amount of economic gain to be achieved with a budgetary constraint of $100,000 were both branch and density (Table 11.8). This assumes that 50 trees per family and 10 trees per family be assessed for each of the total 100 families for branch and density respectively. Considering the cost of assessment, the gain predicted from measuring 5 trees per family for length ($1.1M) was not as efficient compared with the cost-to predicted gain ratios of branch and density (Table 11.8). A tree breeder utilising this strategy may decide to forgo an assessment of tracheid length, to achieve a slightly lower *Present-Value* gain of $9.7M, but at a 25% reduced assessment cost of $75,000.

11.4 Conclusion

The exploration of multi-trait combined selection options (Table 11.5) demonstrated the importance of wood density to the enterprise as currently defined. In general, all wood and tracheid properties examined as selection traits resulted in

substantial increases in economic gain (estimated as *Profitability Index*). Due to the adverse correlations between wood brightness and basic density, however, the importance of improving wood brightness on enterprise profitability is not as attractive as it appeared in Chapter 8. Improvements in branch index were also shown to have a significant impact on the predicted economic gains (Table 11.8). However, improvements in growth were shown to have only a small impact on enterprise profitability overall.

The issue of age-age correlation in the construction of selection indices was ignored in the present work. This is a major assumption but seems justified considering the equivalence between an index accounting for this age related effect and a simpler index investigated in Chapter 10.

Table 11.5 suggests that if density and length were included as family-means, a substantial loss in expected gain would result (74% and 82% of the gain predicted from individual-tree assessments respectively). However, the other more costly-to-measure wood traits (coarse and bright) may be included as family-means with only limited losses in expected gain (92% and 90% respectively).

An optimum selection strategy was identified given a total budget of $100,000 for trait assessments at selection age 10 years (Table 11.8). The strategy opts to select 50 individual trees out of a possible 5000 from a breeding population of 100 families, of which 50 trees per family should be assessed for dbh and branch, 25 trees per family for stem, 10 trees per family for density, and 5 trees per family for length.

Chapter 12

The estimation of genetic parameters and breeding values for diameter and survival traits across two sites in *Eucalyptus nitens*

This chapter has been published as an industry technical report:
Chambers, P.G.S. and Greaves, B.L. (1999). The estimation of genetic parameters and breeding values for diameter and survival traits across two sites in *Eucalyptus nitens*. *Southern Tree Breeding Association Technical Report*, February 1999, 60 pages.
For reasons of confidentiality, family abbreviations have been changed and lists of individual and family breeding values (included as appendices in the original report) deleted.

12.1 Introduction

In the current study, we have examined the genetic control of diameter growth (hereafter abbreviated as dbh) and survival (selection criteria for volume per hectare) across two sites in southern central Tasmania, established by ANM. Breeding values were generated for individual trees and for families for both dbh and survival at 5 years.

Breeding values for volume per hectare at 15 years, and economic merit were estimated for each tree and family from estimated breeding values for dbh and

survival and assumed genetic parameters. The impact on breeding values of not taking some account of survival ability within high mortality sites is investigated.

12.2 Genetic Material and Trial Information

12.2.1 Genetic Material

The progeny in this study were obtained from a collection by Chris O'Connor prior to 1992. It consisted of 112 open-pollinated families of *Eucalyptus nitens*. Documentation provided by the STBA indicated that there were only 92 and then, in conflict with this, 100 open-pollinated families represented in the data. On careful examination of the data provided however, the number of families was 112. Some of this number may have included *Eucalyptus regnans* families planted within each trial to fill in spatial 'gaps', but this could not be confirmed and 112 families were included in the analysis.

12.2.2 Trial Sites, Design and Measurements

ANM Forest Management established the two trials included in this study. The first trial XA-03 (Site 1) was established at Tarraleah and the second trial XA-04 (Site 2) was established in the Florentine Valley (Jungle) in central southern Tasmania. Each trial contained 4 replicates with 12 incomplete blocks of 8 families in 5-tree line plots. The data analysed consisted of 5-year diameter (hereafter dbh) and height measurements. This was received in the form of two excel spreadsheets (Xa0397.xls and Xa0497.xls) from Sandra Hetherington. Survival was assessed from the data provided as the presence or absence of a dbh measurement at age 5. Table 12.1 provides a summary of the trial design and trait characteristics.

Table 12.1- Summary of trial design characteristics and traits analysed.

Trial	No. Records	No. Families	Mean dbh (±s.d.)	Mean survival (±s.d.)
Site 1(XA-03) Tarraleah	1823	106	12.08 ± 3.07	0.77 ± 0.42
Site 2 (XA-04) Florentine Valley	1906	97	11.17 ± 2.98	0.50 ± 0.49
Combined Analysis	3729	112	11.72 ± 3.06	0.63 ± 0.48

12.2.3 Adjustment for Phenotypic Standard Deviation by Site

The observed standard deviations for dbh and survival are shown in Table 12.1. Due to the similarity of variation for dbh and survival across both sites, no adjustment was deemed necessary to standardise the data for combined site analysis.

12.2.3 Data Checking

From the raw data received, 98 records were excluded from the analysis in trial XA-03 (Site 1) and 8 records were excluded from trial XA-04 (Site 2). For the majority, records were excluded due to missing family codes. Relevant data and model checking was employed to check the assumptions used in this analysis, namely Normality and equality of variances. A plot of residuals versus fitted values showed one potential outlier in the data, but this record aside, showed no evidence of variance inequality. The Normal probability plot further suggested that the following record be excluded from the analysis:

site	trial	fam. code	rep	inc. block	dbh	fitted value	residual
1	XA-03	AA2	3	7	2.0	15.23	-5.23

This value did not fit well with the general trend of the data and may need to be rechecked.

12.3 Method Summary

The analysis method followed the following general steps:

- calculation of genetic parameters across both sites for dbh and survival;
- calculation of genetic parameters within each site for dbh and survival;
- estimation (as *BLUPs*) of family and individual-tree breeding values (*EBVs*) for dbh and survival (selection criteria) across both sites at age 5 years;
- conversion of *EBVs* for the two selection criteria into an estimated *EBV* for the current STBA breeding objective trait: volume per hectare at age 15 years, taking account of the assumed age-age correlations for growth;
- calculation of the economic merit of each tree and family based on the STBA economic weight for volume per hectare at 15 years.

12.4 Genetic Parameter Estimation

12.4.1 Combined Site Analysis

12.4.1.1 Statistical Models and Methods

Estimates of variance components and heritabilities for dbh and survival across the two sites were obtained by REML methods using the ASREML program (Gilmour *et al.* 1998). As a check, heritabilities were also estimated using the SAS VARCOMP procedure (SAS 1989). In all cases, chance components were assumed to take independent values from a common Normal distribution.

Three models were fitted to the data in the calculation of variance components.

1). A family based model, defined as:

$$\mathbf{y} = \mu + \mathbf{Xb} + \mathbf{Zu} + \mathbf{Ik} + \mathbf{e} \qquad (12.1)$$

where:

- **y** is the vector for *n* observations for dbh and survival;
- **b** is the vector for the fixed effect, namely a derived variable which incorporates site, replicate and incomplete block information;
- **u** is the vector for the family (or GCA) effect;
- **k** is the vector for the site*family interaction effect;
- **e** is the vector for residuals;and
- **X**, **Z**, **I** are incidence matrices for the fixed and random effects respectively.

2). A family based model which did not take into account the adjustment for families within different incomplete blocks (due to the level of mortality across both sites and hence the possibility of failure of the incomplete block experimental design due to this mortality):

$$\mathbf{y} = \mu + \mathbf{Hk} + \mathbf{Zu} + \mathbf{Ik} + \mathbf{e} \qquad (12.2)$$

where:

- vectors and matrices are defined above, except:

- **k** is the new vector for the fixed effect, a derived variable which incorporates just site and replicate within site; and
- **H** is the corresponding incidence matrix for the fixed effect vector, *k*.

3). An individual tree model which did not contain a site*family interaction effect (due to problems with the convergence of likelihoods in solving the given set of equations):

$$\mathbf{y} = \mu + \mathbf{Xb} + \mathbf{Da} + \mathbf{e} \qquad (12.3)$$

where:

- vectors and matrices are defined above, except:
- **a** is the vector for the individual tree (additive genetic) effect, and
- **D** is the corresponding incidence matrix for the additive genetic effect, **a**.

12.4.1.2 Calculation of Heritability

Narrow-sense heritability estimates for dbh from Equations 12.1 and 12.2 were calculated as:

$$h^2 = \frac{V_f}{r.(V_f + V_k + V_{res})} \qquad (12.4)$$

where:

- h^2 is the heritability;
- V_f is the variance for the family (GCA) effects;
- V_k is the variance for the family*site interaction effect;
- V_{res} is the portion of unexplained residual variance; and
- r is the coefficient of relationship assumed to be 0.4 after Volker *et al.* (1990).

Heritability estimates for dbh estimated from Model Equation 12.3 were calculated as:

$$h^2 = \frac{V_a}{(V_a + V_{res})} \times \frac{r_{op}}{r} \qquad (12.5)$$

where:

- parameters are as defined previously, except:
- V_a is the variance due to additive genetic effects; and
- r_{op} is the coefficient of relationship for fully outcrossed open-pollinated individuals: 0.25.

Equations 12.4 and 12.5 follow adjustments made for related mating in open-pollinated sibs, assuming the average relationship amongst sibs is 0.4, equating to a selfing rate of approximately 30% (Volker *et al.* 1990). Standard errors were calculated from the variance components using the post processing facility of ASREML.

12.4.1.3 Genetic and Phenotypic Correlations

Variances and covariances between dbh and survival were estimated from a bivariate analysis following Model Equations 12.1 and 12.3 only. Due to the fact that two different sites were involved in this analysis, the residual covariance was constrained to a small value (approaching zero). Genetic correlations were calculated from Model Equation 12.1 as:

$$r_g = \frac{\mathrm{cov}(f_{dbh}, f_{survival})}{\sqrt{V_{f_{dbh}} . V_{f_{survival}}}} \qquad (12.6)$$

where:

- r_g is the genetic correlation between dbh and survival; and
- $\mathrm{cov}(f_{dbh,}, f_{survival})$ is the covariance between family effects for dbh and survival.

Genetic correlations calculated from the individual tree analysis (Model Equation 12.3) were calculated from:

$$r_g = \frac{\mathrm{cov}(a_{dbh}, a_{survival})}{\sqrt{V_{a_{dbh}} . V_{a_{survival}}}} \qquad (12.7)$$

where:

- parameters are defined previously, except:
- $\mathrm{cov}(a_{dbh,}, a_{survival})$ is the covariance between additive genetic effects for dbh and survival.

12.4.2 Single Site Analysis

12.4.2.1 Statistical Models and Methods

Estimates of variance components and heritabilities for dbh and survival within each site were obtained using the SAS VARCOMP procedure (SAS 1989). In all cases, chance components were assumed to take independent values from a common Normal distribution.

Two different models were fitted to the data in the calculation of variance components.

1). A family based model, defined as:

$$\mathbf{y} = \mu + \mathbf{Xb} + \mathbf{Zu} + \mathbf{e} \qquad (12.8)$$

where:

- **y** is the vector for *n* observations for dbh and survival;
- **b** is the vector for the fixed effect, a derived variable which incorporates replicate within site and incomplete block information;
- **u** is the vector for the family (or GCA) effect; and
- **X** and **Z** are incidence matrices for the fixed and random effects respectively.

2). A second family based model was applied which included a fixed effect for replicate (ignoring any incomplete block within replicate effects):

$$\mathbf{y} = \mu + \mathbf{Rs} + \mathbf{Zu} + \mathbf{e} \qquad (12.9)$$

where:

- vectors and matrices are defined previously, except:
- **s** is the new vector for the fixed effect for replicate within site; and
- **R** is the corresponding incidence matrix for the fixed effect vector, **k**.

12.4.2.2 Calculation of Heritability

Narrow-sense heritability estimates for dbh within each site were calculated as:

$$h^2 = \frac{V_f}{r.(V_f + V_{res})} \qquad (12.10)$$

where:

- h^2 is the heritability;
- V_f is the variance for the family (GCA) effects;
- V_{res} is the portion of unexplained residual variance; and
- r is the coefficient of relationship assumed to be 0.4 after Volker *et al.* (1990).

Standard errors were also calculated from the variance components using the post processing facility of ASREML. It must be noted that estimates of heritability both within and across sites are based on open-pollinated data. The components used in calculating them hence contain both additive and non-additive components and may be inflated by dominance and related effects or inbreeding. There has been some evidence in the literature that the non-additive component may be large for growth traits (Hodge *et al.* 1996).

12.4.3 Heritability of Survival & Phenotypic Correlation with DBH

The heritability of survival was estimated as for dbh in each case above (equations 12.4, 12.5 and 12.10). These estimates of heritability however, were based on a binomial distribution, where the estimated variances for each effect differ according to the mean. These estimates must be converted to an assumed underlying continuous scale for comparison across sites (see Chambers *et al.* 1996), following:

$$h_n^2 = h_{0/1}^2 \frac{p(1-p)}{z^2} \qquad (12.11)$$

where:

- h^2_n is the heritability for survival on the underlying scale (assuming survival is normally distributed on this scale);
- $h^2_{0/1}$ is the heritability on the observed binomial scale (obtained from equations 12.4, 12.5 and 12.10);
- p is the proportion of trees surviving; and
- z is the height of the ordinate at the threshold corresponding to the proportion of surviving trees.

Although genetic correlations between binomial and normally distributed traits (i.e. survival and dbh) are equivalent on the binomial and assumed underlying scales, phenotypic correlations must be adjusted to the underlying scale for comparison across trials (Olausson and Rönningen 1975).

Phenotypic correlations between dbh and survival were calculated from:

$$r_n = r_{0/1}\left[\frac{p(1-p)}{z^2}\right]^{\frac{1}{2}} \qquad (12.12)$$

where:

- r_n is the phenotypic correlation between dbh and survival on the underlying continuous scale;
- $r_{0/1}$ is the phenotypic correlation between dbh and survival as calculated on the binomial scale; and
- p and z are as previously defined in Equation 12.11.

12.4.4 Results

Overall means of dbh and survival and their respective standard deviations are given in Table 12.1. Both sites showed good tree growth, with Site 1 exhibiting slightly faster growth (mean dbh = 12.08) than Site 2 (mean dbh = 11.17) at age five years. Survival, however, was low in both sites, with only 50% of planted trees surviving to age 5 at Site 2 and 77% surviving to age 5 at Site 1. From field notes supplied by Peter Gore[#], the mortality at Site 1 was patchy, indicating that some regions within that site were not good for planting. Autumn gum moth damage was reported to have occurred at both sites, with some substantial weed competition reported in Site 1.

12.4.4.1 Combined Site Analysis

Variance components, individual heritabilities and their standard errors for dbh and survival for the combined site analysis, using a family (GCA) based model (Equation 12.1) and an individual tree model (Equation 12.3) are given in Table 12.2.

[#] Eucalypt Program Manager, STBA

Table 12.2- Trait means and estimates of additive genetic (V_a), residual (V_{res}) and total phenotypic (V_{total}) variances and corresponding heritabilities for dbh and survival across two sites at age 5 years. For survival, the heritability estimate must be converted to an underlying, continuous scale (h^2_n): see text.

Model	Trait	Mean	V_a	$V_{site*fam}$	V_{res}	V_{total}	h^2 (s.e.)	h^2_n
1	dbh	11.72	1.25	0.00	7.0	8.26	0.15 (0.04)	-
	survival	0.63	0.03	0.02	0.18	0.21	0.14 (0.05)	0.2
3	dbh	11.72	1.22	-	7.05	8.27	0.15 (0.04)	-
	survival	0.63	0.05	-	0.15	0.2	0.25 (0.04)	0.41

Phenotypic and genetic correlations between dbh and survival for the combined site analysis using Model Equations 12.1 and 12.3 are shown in Table 12.3.

Table 12.3- Phenotypic correlation on the binomial ($r_{0/1}$) and underlying continuous scales (r_n) and genetic correlation (r_g) between survival and growth across 2 sites at age 5 years.

Model	Traits	r_g (s.e.)	$r_{0/1}$ (s.e.)	r_n
1	dbh_survival	-0.01 (0.26)	-0.02 (0.03)	-0.17
3	dbh_survival	-0.18 (0.16)	-0.03 (0.03)	-0.21

12.4.4.2 Single Site Analysis

Variance components, individual heritabilities and their standard errors for dbh and survival within each site are given in Table 12.4. These estimates are based on the within-site family effect models (Equations 12.9 and 12.10).

Table 12.4- Trait means and estimates of additive genetic (V_a), residual (V_{res}) and total phenotypic (V_{total}) variances and corresponding heritabilities for dbh and survival within each site at age 5 years. For survival, the heritability estimate must be converted to an underlying, continuous scale (h^2_n): see text.

Site	Model	Trait	Mean	V_a	V_{res}	V_{total}	h^2 (s.e.)	h^2_n
1	8	dbh	12.08	1.25	6.92	8.17	0.15 (0.04)	
		survival	0.77	0.05	0.11	0.16	0.32 (0.04)	0.65
	9	*dbh*		*1.79*	*7.28*	*9.07*	*0.2 (0.04)*	
		survival		*0.05*	*0.10*	*0.16*	*0.29 (0.05)*	*0.59*
2	8	dbh	11.17	0.79	7.36	8.15	0.10 (0.04)	
		survival	0.50	0.08	0.15	0.24	0.36 (0.04)	0.56
	9	*dbh*		*0.97*	*7.33*	*8.31*	*0.17 (0.04)*	
		survival		*0.09*	*0.16*	*0.25*	*0.36 (0.06)*	*0.57*

12.5 Breeding Value Estimation

Individual tree and family breeding values (*EBVs*) for dbh and survival were simultaneously estimated across both sites as BLUPs using ASREML (Gilmour *et al.* 1998). Family level and individual tree *EBVs* were estimated following models 4.1 and 4.3 respectively. The genetic and residual covariance matrices used in the generation of these *EBVs* were derived from the calculated genetic parameters as listed below:

VARIANCE COMPONENT	TRAIT		
	dbh	dbh-surv (COV)	survival
V_a	1.229	-0.045	0.051
$V_{fam*site}$	0.002	0.000	0.017
$V_{residual}$	7.052	0.000	0.149

12.5.1 Family Level Breeding Values

12.5.1.1 Estimates of Basal Area

From the breeding values of dbh and survival, an estimate of basal area (m^2/ha) was established following the formula:

$$BA5_{est} = \frac{\left\{\pi \frac{(\bar{x}_{dbh5} + EBV_{dbh5})^2}{4}\right\} * \left\{1000(\bar{x}_{survival5} + EBV_{survival5})\right\}}{10000} \quad (12.13)$$

where:

- $BA5_{est}$ is the basal area of the stand, assuming an initial stocking of 1000 stems per hectare at age 5 years;
- $\bar{x}_{dbh5}$ and $\bar{x}_{survival5}$ are the family means for dbh and survival respectively, across both sites; and
- EBV_{dbh5} and $EBV_{survival5}$ are the estimated family breeding values for dbh and survival respectively, across both sites.

Estimated breeding values for *BA5* were calculated as deviations from the mean after:

$$EBV_{BA5} = BA5_{est} - \overline{BA5_{est}} \quad (12.14)$$

where:

- EBV_{BA5} is the standardised deviation of each family's estimated basal area from the sample mean ($\overline{BA5_{est}}$) at age 5 years.

12.5.1.2 Conversion of Basal Area to Volume per Hectare

The estimated family breeding values for basal area (EBV_{BA5}) were converted to a breeding value estimate of the current STBA breeding objective trait, volume per hectare at age 15, following:

$$EBV_{VOL15} = \frac{EBV_{BA5}}{\sigma_{fam.BA5}} * r_{BA5.VOL15} * \sigma_{fam.VOL15} \quad (12.15)$$

where:

- EBV_{VOL15} is the estimated breeding value for the STBA objective trait, volume at rotation age of 15 years, in m^3/ha;
- $\sigma_{fam.BA5}$ is the estimated between-family standard deviation for *BA5* calculated as the standard deviation of family EBV_{BA5} estimates;
- $r_{BA5.VOL15}$ is the age-age correlation in growth calculated using the age-age correlation trend used by Greaves *et al.* (in press) to be 0.8; and
- $\sigma_{fam.VOL15}$ is the assumed between-family standard deviation of the STBA objective trait, volume at rotation age of 15 years, calculated after:

$$\sigma_{fam.VOL15} = \sqrt{\sigma^2_{a.VOL15} * r} \qquad (12.16)$$

where:

- $\sigma^2_{a.VOL15}$ is the assumed addition variance for VOL15 in *E. nitens* of 2025 (Jarvis and Borralho 1995); and
- r is the coefficient of relationship, assumed to be 0.4 after Volker *et al.* (1990).

12.5.1.3 Estimation of Economic Merit

The economic merit of each family for VOL_{15} was calculated from:

$$EM_{VOL15} = w * EBV_{VOL15} \qquad (12.17)$$

where:

- w is the STBA economic weight for *VOL* at age 15 for *E. nitens*, assumed to be \$0.27 (m^3/ha) (Jarvis and Borralho 1995); and
- EM_{VOL15} is the economic merit, i.e. the monetary value in real terms for each family.

12.5.2 Individual Breeding Values

12.5.2.1 Estimates of Basal Area

From the estimated individual tree breeding values of dbh and survival, an estimate of basal area (m^2/ha) was established following the formula:

$$BA5_{est} = \frac{\left\{\pi \frac{(\bar{x}_{dbh5} + EBV_{dbh5})^2}{4}\right\} * \left\{1000(\bar{x}_{survival5} + EBV_{survival5})\right\}}{10000} \quad (12.18)$$

where:

- $BA5_{est}$ is the basal area of the stand, assuming an initial stocking of 1000 stems per hectare at age 5 years;
- $\bar{x}_{dbh5}$ and $\bar{x}_{survival5}$ are the overall means for dbh and survival respectively, across both sites; and
- EBV_{dbh5} and $EBV_{survival5}$ are the estimated individual tree breeding values for dbh and survival respectively, across both sites.

Estimated breeding values for *BA5* were calculated as deviations from the mean after:

$$EBV_{BA5} = BA5_{est} - \overline{BA5}_{est} \quad (12.19)$$

where

- EBV_{BA5} is the standardised deviation of each individual's estimated basal area from the sample mean ($\overline{BA5}_{est}$) at age 5 years.

12.5.2.2 Conversion of Basal Area to Volume per Hectare

The standardised estimates of basal area (EBV_{BA5}) were converted to a breeding value estimate of the current STBA breeding objective trait, volume per hectare at age 15, following:

$$EBV_{VOL15} = \frac{EBV_{BA5}}{\sigma_{a.BA5}} * r_{BA5.VOL15} * \sigma_{a.VOL15} \quad (12.20)$$

where:

- EBV_{VOL15} is the estimated breeding value for the STBA objective trait, volume at rotation age of 15 years, in m^3/ha; and
- $\sigma_{a.BA5}$ is the additive standard deviation for *BA5* estimated as:

$$\sigma_{a.BA5} = \sqrt{\frac{\sigma^2_{fam.BA5}}{r}} \quad (12.21)$$

- $r_{BA5.VOL15}$ is the age-age correlation in growth calculated using the age-age correlation trend used by Greaves *et al.* (in press) to be 0.8; and
- $\sigma_{a.VOL15}$ is the assumed additive standard deviation of the STBA objective trait, volume at rotation age of 15 years (given by Jarvis and Borralho (1995) for *E. nitens* as 45).

12.5.2.3 Estimation of Economic Merit

The economic merit of each individual for VOL_{15} was calculated from:

$$EM_{VOL15} = w * EBV_{VOL15} \qquad (12.22)$$

where:

- w is the STBA economic weight for *VOL* at age 15 for *E. nitens*, assumed to be \$0.27 m^3/ha (Jarvis and Borralho 1995); and
- EM_{VOL15} is the economic merit, i.e. the monetary value in real terms for each family.

12.5.3 Results

12.5.3.1 Family Breeding Values

Estimated family breeding values for dbh, survival and basal area at a selection age of 5 years and the estimated breeding values for volume per hectare at a rotation age of 15 years are presented as:

- Top 10 families for dbh (Table 12.5)
- Top 10 families for volume per hectare (Table 12.6)

Table 12.5- Family breeding values (BLUPs), with their respective standard errors for dbh, survival and basal area (EBV_{BA5}) at age 5 years, estimated breeding values for volume at age 15 years (EBV_{VOL15}) and the economic merit for each family based on volume at 15 years (EM_{VOL15}). The top 10 families are shown as ranked according to BLUP estimates for dbh.

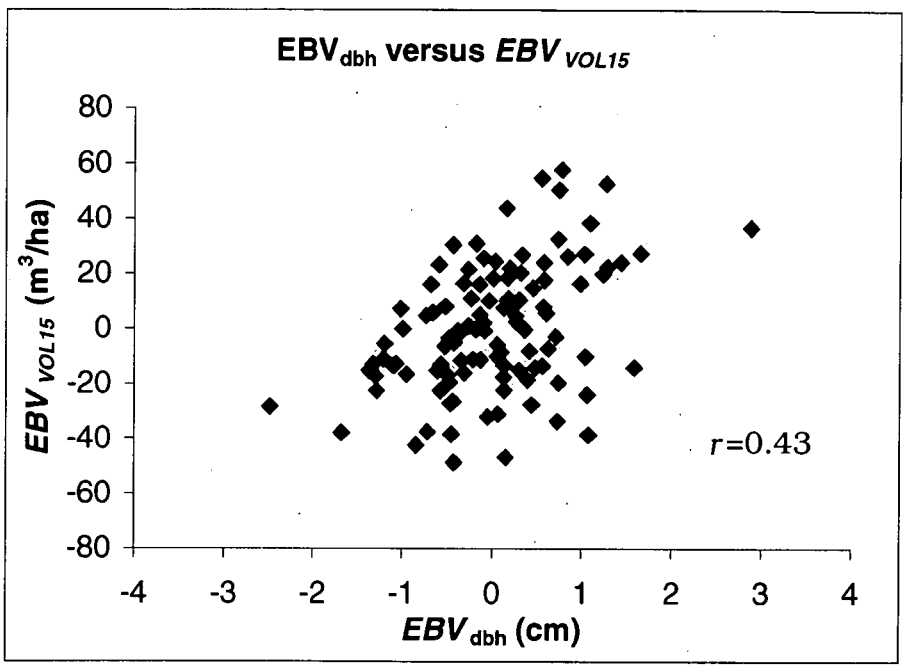
Family	DBH (cm)			Survival (proportion)			Basal Area (m^2/ha)		VOL/HA (m^3/ha)	
	BLUP	(s.e.)	Rank	BLUP	(s.e.)	Rank	EBV_{BA5}	Rank	EBV_{VOL15}	EM_{VOL15}
AA2	2.877	0.595	**1**	-0.078	0.103	82	1.61	7	36.658	**9.9**
JJ2	1.648	0.658	**2**	-0.011	0.116	66	1.2	11	27.328	**7.38**
HH1	1.581	0.891	**3**	-0.227	0.116	105	-0.623	81	-14.175	**-3.83**
DD2	1.431	0.6	**4**	-0.008	0.109	63	1.051	18	23.935	**6.46**
HH2	1.281	0.692	**5**	-0.001	0.116	61	0.982	20	22.352	**6.04**
FF1	1.263	0.482	**6**	0.172	0.104	12	2.312	3	52.641	**14.21**
GG2	1.225	0.556	**7**	-0.01	0.104	65	0.866	24	19.717	**5.32**
GG1	1.085	0.493	**8**	0.113	0.104	25	1.684	6	38.346	**10.35**
CC2	1.071	0.992	**9**	-0.333	0.111	112	-1.701	109	-38.72	**-10.45**
EE1	1.056	0.821	**10**	-0.246	0.144	108	-1.05	98	-23.917	**-6.46**

Table 12.6- Family breeding values (BLUPs), with their respective standard errors for dbh, survival and basal area (EBV_{BA5}) at age 5 years, estimated breeding values for volume at age 15 years (EBV_{VOL15}) and the economic merit for each family based on volume at 15 years (EM_{VOL15}). The top 10 families are shown as ranked according to EBV_{VOL15}.

Family	DBH (cm)			Survival (proportion)			Basal Area (m^2/ha)		VOL/HA (m^3/ha)	
	BLUP	(s.e.)	Rank	BLUP	(s.e.)	Rank	EBV_{BA5}	Rank	EBV_{VOL15}	EM_{VOL15}
DD3	0.773	0.483	15	0.271	0.104	4	2.538	**1**	57.776	**15.6**
DD5	0.549	0.815	27	0.286	0.15	1	2.401	**2**	54.677	**14.76**
FF1	1.263	0.482	6	0.172	0.104	12	2.312	**3**	52.641	**14.21**
EE2	0.744	0.511	16	0.23	0.104	7	2.215	**4**	50.428	**13.62**
CC2	0.159	0.474	47	0.277	0.104	3	1.919	**5**	43.684	**11.79**
GG1	1.085	0.493	8	0.113	0.104	25	1.684	**6**	38.346	**10.35**
AA2	2.877	0.595	1	-0.078	0.103	82	1.61	**7**	36.658	**9.9**
AA1	0.733	0.51	18	0.122	0.104	23	1.428	**8**	32.509	**8.78**
DD4	-0.185	0.497	67	0.244	0.104	6	1.356	**9**	30.885	**8.34**
BB1	-0.438	0.5	81	0.281	0.106	2	1.329	**10**	30.258	**8.17**

Figure 12.1 shows a plot of the estimated breeding values for dbh (EBV_{dbh}) versus the estimated breeding values for volume(EBV_{VOL15}). This figure provides a measure of the degree of similarity between selections based solely on dbh, compared with selections based on a volume estimate (which accounts for the high degree of mortality at both sites). The correlation between EBV_{dbh} and EBV_{VOL15} was only moderate, at 0.43.

Figure 12.1- Plot of estimated breeding values for dbh at age 5 years (EBV_{dbh}) versus estimated breeding values for volume at age 15 years (EBV_{VOL15}).



12.5.3.2 Individual Tree Breeding Values

Estimated individual tree breeding values for dbh, survival and basal area at a selection age of 5 years and the estimated breeding values for volume per hectare at a rotation age of 15 years are presented as:

- Top 20 individuals for dbh (Table 12.7)
- Top 20 individuals for volume per hectare (Table 12.8)

Table 12.7- Individual tree breeding values (BLUPs), with their respective standard errors for dbh, survival and basal area (EBV_{BA5}) at age 5 years, estimated breeding values for volume at age 15 years (EBV_{VOL15}) and the economic merit for each tree based on volume at 15 years (EM_{VOL15}). The top 20 individuals are shown as ranked according to dbh.

SITE	FAM	TREE	DBH (cm)			Survival (propn.)			Basal Area (m^2)			VOL/HA (m^3/ha)	
			BLUP	(s.e.)	Rank	BLUP	(s.e.)	Rank	$BA5_{est}$	EBV_{BA5}	Rank	EBV_{VOL15}	EM_{VOL15}
1	GG3	5	3.59	1.158	**1**	-0.003	0.206	2141	12.436	1.899	10	68.348	**18.45**
1	AA2	4	3.406	1.158	**2**	0	0.206	2133	12.191	1.807	20	65.05	**17.56**
2	FF1	5	2.518	1.159	**3**	0.038	0.205	1926	11.402	1.512	80	54.421	**14.69**
1	AA2	3	2.439	1.16	**4**	0.022	0.206	2034	11.022	1.369	139	49.289	**13.31**
2	AA2	4	2.233	1.171	**5**	0.119	0.206	1252	12.198	1.81	19	65.147	**17.59**
2	AA2	5	2.194	1.161	**6**	0.112	0.206	1316	12.013	1.74	29	62.651	**16.92**
2	AA2	4	2.186	1.159	**7**	0.043	0.205	1878	10.957	1.345	153	48.411	**13.07**
2	AA2	1	2.153	1.164	**8**	0.077	0.206	1661	11.417	1.517	77	54.623	**14.75**
2	AA2	1	2.139	1.161	**9**	0.113	0.206	1313	11.932	1.71	36	61.557	**16.62**
1	AA2	5	2.106	1.16	**10**	0.027	0.206	1999	10.588	1.207	228	43.445	**11.73**
1	DD2	4	2.085	1.162	**11**	0.098	0.207	1451	11.627	1.596	56	57.451	**15.51**
2	JJ2	1	2.068	1.169	**12**	0.004	0.208	2109	10.197	1.06	338	38.171	**10.31**
2	AA2	1	1.975	1.171	**13**	0.123	0.206	1219	11.812	1.665	43	59.937	**16.18**
1	AA2	1	1.952	1.291	**14**	-0.309	0.206	3516	5.428	-0.725	2954	-26.112	**-7.05**
1	AA2	2	1.952	1.291	**15**	-0.309	0.206	3517	5.428	-0.725	2955	-26.112	**-7.05**
1	AA2	3	1.952	1.291	**16**	-0.309	0.206	3518	5.428	-0.725	2956	-26.112	**-7.05**
1	AA2	4	1.948	1.291	**17**	-0.302	0.206	3484	5.519	-0.691	2893	-24.889	**-6.72**
2	AA2	2	1.938	1.291	**18**	-0.285	0.206	3439	5.767	-0.598	2752	-21.543	**-5.82**
2	AA2	3	1.938	1.291	**19**	-0.285	0.206	3440	5.767	-0.598	2753	-21.543	**-5.82**
1	AA2	1	1.932	1.291	**20**	-0.273	0.206	3383	5.933	-0.536	2658	-19.303	**-5.21**

Table 12.8- Individual tree breeding values (BLUPs), with their respective standard errors for dbh, survival and basal area (EBV_{BA5}) at age 5 years, estimated breeding values for volume at age 15 years (EBV_{VOL15}) and the economic merit for each tree based on volume at 15 years (EM_{VOL15}). The top 20 individuals are shown as ranked according to to EBV_{VOL15}.

SITE	FAM	TREE	DBH (cm)			Survival (propn.)			Basal Area (m^2)			VOL/HA (m^3/ha)	
			BLUP	(s.e.)	Rank	BLUP	(s.e.)	Rank	$BA5_{est}$	EBV_{BA5}	Rank	EBV_{VOL15}	EM_{VOL15}
2	DD3	3	1.323	1.15	77	0.367	0.206	15	13.973	2.474	**1**	89.075	**24.05**
2	CC2	1	0.9	1.146	244	0.373	0.206	13	13.147	2.165	**2**	77.938	**21.04**
2	EE2	3	0.805	1.158	339	0.361	0.206	20	12.809	2.038	**3**	73.376	**19.81**
1	DD3	1	1.507	1.142	53	0.252	0.206	280	12.778	2.027	**4**	72.963	**19.7**
2	EE2	2	1.382	1.149	67	0.269	0.206	191	12.772	2.025	**5**	72.885	**19.68**
2	DD3	2	0.677	1.15	461	0.378	0.206	9	12.746	2.015	**6**	72.527	**19.58**
2	DD1	1	1.124	1.129	136	0.289	0.204	138	12.536	1.936	**7**	69.698	**18.82**
2	AA1	2	1.198	1.153	108	0.274	0.206	181	12.488	1.918	**8**	69.055	**18.64**
2	GG1	2	1.439	1.147	59	0.238	0.206	356	12.465	1.909	**9**	68.741	**18.56**
1	GG3	5	3.59	1.158	1	-0.003	0.206	2141	12.436	1.899	**10**	68.348	**18.45**
2	FF1	2	1.054	1.143	175	0.285	0.206	150	12.346	1.865	**11**	67.136	**18.13**
2	GG1	4	1.347	1.147	75	0.24	0.206	345	12.311	1.852	**12**	66.671	**18**
2	EE2	3	0.476	1.152	806	0.375	0.206	12	12.309	1.851	**13**	66.645	**17.99**
2	JJ1	4	1.075	1.16	159	0.279	0.207	163	12.307	1.85	**14**	66.609	**17.98**
2	FF1	1	0.998	1.143	197	0.286	0.206	148	12.249	1.829	**15**	65.84	**17.78**
2	DD3	4	0.579	1.146	579	0.352	0.206	28	12.245	1.827	**16**	65.784	**17.76**
2	EE2	1	0.44	1.152	872	0.376	0.206	11	12.242	1.826	**17**	65.736	**17.75**
2	DD3	2	0.606	1.146	532	0.345	0.206	36	12.214	1.816	**18**	65.365	**17.65**
2	AA2	4	2.233	1.171	5	0.119	0.206	1252	12.198	1.81	**19**	65.147	**17.59**
1	AA2	4	3.406	1.158	2	0	0.206	2133	12.191	1.807	**20**	65.05	**17.56**

The rank correlation between individual tree breeding values for dbh and estimated breeding values for volume was calculated to be 0.41.

12.6 Discussion and Conclusions

12.6.1 Genetic Parameters

The heritability for dbh across both sites (Table 12.2) was shown to be 0.15. This is much lower than the STBA reported heritability by Jarvis and Borralho (1993) of 0.38 for dbh in *Eucalyptus nitens* in Tasmania. The lower estimate obtained in this study is likely to be a result of the poor survival across both sites. Due to the effect of spacial heterogeneity, individual trees would be under varying degrees of competition, resulting in an increase in the within-family variation, and hence a decrease in the heritability ratio.

The heritability for survival across both sites was moderate (Table 12.2), but varied depending on which model was used to analyse the data. The individual tree model (Equation 12.3) showed a higher heritability on the underlying scale (h^2_n=0.41) than the family model (Equation 12.1)(h^2_n=0.20). The variance components of both models were evaluated to explain why this discrepancy may have occurred. It seems that in the family based model the variance attributed to the site*family interaction effect is 'leeched' from the additive genetic variance. It is not known why this is occurring, as the variation should have come from the unexplained residual component (V_{res}). However, the variation explained by the site*family effect points to a significant G*E interaction for survival in this analysis.

The phenotypic correlation (adjusted to an underlying, continuous scale) between dbh and survival across both sites was slightly negative, as was the genetic correlation (Table 12.3), however neither was significantly different from zero (as judged by confidence intervals of twice the predicted standard error). Nevertheless, the consistent negative trend for phenotypic and genetic correlations using both an individual tree and family based model may suggest a slight tendency across sites for the the slower growing trees and families to have a greater chance of survival to age 5 years.

The heritability of dbh within each site was also low, ranging between 0.10 and 0.20 (Table 12.4), and similar to the estimate across sites (Table 12.2). The heritability for dbh increased when using a model which did not account for any differences due to the fixed incomplete block effect. In fact, these estimates should be lower than when the incomplete block effect is included in the model as the

differences should come out in the residual variance. The fact that this is occurring may be an indication of the failure of the experimental design to cope with the high level of mortality within each site.

Within each site, survival was shown to be very highly heritable (h^2_n=0.65 for site 1, and 0.57 for site 2) (Table 12.4). When compared with the heritability estimate for survival across sites (0.41 using the individual tree model), and the evidence of a significant G*E effect (Table 12.2), this would indicate that the particular agents which are causing mortality at each site are different.

12.6.2 Estimated Breeding Values

The generation of family breeding values showed the top 10 ranking families for dbh (Table 12.5). The ranking of families based on dbh did not correlate well (r=0.43) with the ranking of familes for volume at rotation age due to the poor survival across sites (Table 12.6). Table 12.5 shows that if using dbh at 5 years as a selection trait for volume per hectare at 15 years, only 3 families would be selected (*AA2*, *FF1* and *GG1*) which rank amongst the top 20 breeding values for volume. *AA2* showed outstanding dbh growth, however due to poorer survival ability was only ranked 7th overall for volume per hectare. The best ranking family for volume per hectare (which accounts for the survival ability of the respective families in addition to dbh growth) was *DD3* (Table 12.6) which ranks 15th overall for dbh. The relationship between breeding values for dbh (EBV_{dbh}) and volume per hectare (EBV_{VOL15}) shows a correlation coefficient of 0.43 (Figure 12.1). This can be interpreted as: selections based upon dbh alone will capture only 43% of the gain in volume per hectare achievable for selection for volume per hectare directly (incoporating dbh and survival).

The estimation of individual tree breeding values showed a similar trend as for family breeding values. Ranking of individuals based on dbh showed a poor correlation with the ranking based on volume per hectare (r=0.42). If selecting solely on dbh at age 5 years, only 3 individuals would be selected which also rank in the top 20 for volume per hectare at 15 years.

From the examination of estimated breeding values for dbh and volume per hectare, it can be seen that unless some account is made for survival ability on sites with high mortality, then only sub-optimal genetic gains will be made.

Chapter 13

An account of the importance of survival in short-rotation breeding programs

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13.1 Introduction

An increase in productivity in plantations is one of the main objectives of tree breeding programs. In the particular case of short rotation plantations, where stocking remains constant from planting to harvest, productivity is dependent on both the volume per tree and the number of trees per unit area which survived to the end of the rotation. Although it has been known for around a century that individual tree volume does depend on spacing (Reineke 1933, Yoda *et al.* 1963, Zeide 1995), volume per hectare reflects both the volume on each tree and the number of trees. Mild mortality in conditions of fully stocked plantations is usually of little concern, as surviving trees will compensate somewhat for their missing neighbours. In short rotation species, in particular in cases of clonal forestry, competition rarely causes mortality (Hardner and Tibbits 1996), and the well documented rules of self-thinning in long rotation conifers (Zeide 1995) do not apply to eucalypts, poplars or acacias harvested at 5 to 15 years. However mortality in such plantations can be considerably affected by ground frost, weed

competition, disease and drought effects during early years after establishment, resulting in loss of productivity and an increase in plantation establishment and growing costs.

Survival can be defined as a measure of adaptability to specific environmental factors, and in that sense, if different factors are known to be of influence, we would have survival for each factor defined as a different trait. Survival has rarely been included in the breeding objective (e.g. Borralho *et al.* 1993, Greaves *et al.* 1996), despite the known variation and some evidence that it is under strong genetic control (Volker *et* al. 1995, Chambers *et al.* 1996). This paper examines the importance of incorporating survival as a selection trait in maximising gains in productivity per unit area on short rotation tree breeding programs, for a range of genetic parameters. The productivity function used was derived for *E. grandis* plantations in South Africa, but the trends should be applicable for most short rotation species. The model accounts for the effect of variation in stocking density on the volume per hectare, and mortality was assumed to be either dispersed or patchy.

13.2 Methods

13.2.1 Volume Function

The volume per hectare at a given age (V_t) was predicted as a function of number of stems per hectare (S) for a given age (t) and site index, using a function of the type: $V_t=f(S,t)$, such that we would expect larger trees if survival is lower. The specific function used in this study was taken from Bredenkamp (1987). It describes an empirical growth model which accounts for the effects of initial stocking density on volume per hectare of *Eucalyptus grandis* in even aged stands. Since there is no inherent mortality process present, such as self-thinnings, mortality due to external environmental effects are expected to be the sole factor affecting the survival of each individual tree. Mean volume per tree was calculated as:

$$\log(V_t) = -5.9482 + 1.7154\log(D_t - 20) + 1.1070\log(H_t) \qquad (13.1)$$

where:

- V_t is an expression of mean tree volume in (m^3) at age t;
- D_t is mean diameter at breast height in millimeters (D_t>20); and

- H_t is mean height in metres.

The variables D_t and H_t are simply a function of age and initial stocking of the stand. Age and stocking are the driving variables for predicting D and H, and the parameters in this study were restricted to a particular site class. Nevertheless, its use is still valid in demonstrating the relative importance of survival as a selection trait. Diameter at breast height was estimated from:

$$\log(D_t) = 0.4342 + 0.2150(t) - 0.0043(t)^2 + 1.2313\log(S) - 0.1019(t)\log(S) + 0.0019(t)^2\log(S) - 0.2128\log(S)^2 + 0.0107(t)\log(S)^2 - 0.0001(t)^2\log(S)^2 \quad (13.2)$$

and height estimated from:

$$\log(H_t) = 1.2522 - 0.0663(t) + 0.0025(t)^2 - 0.4714\log(S) + 0.1447(t)\log(S) - 0.0046(t)^2\log(S) + 0.0702\log(S)^2 - 0.0254(t)\log(S)^2 + 0.0008(t)^2\log(S)^2 \quad (13.3)$$

where:

- t is the stand age in years, and S is the number of stems per hectare.

13.2.2 Breeding Objective

An initial stand density of 1000 trees per hectare was used in this study, with survival ranging between 40% (400 trees per hectare) to 100% (or the 'fully stocked' situation of 1000 trees per hectare). Two scenarios were envisaged relating to the nature of mortality within the simulated stand. The first assumed that mortality was dispersed throughout the stand, thus increasing the average spacing between survivors and enabling trees to 'compensate' for the loss of their neighbours, by increased height and diameter growth, according to Equations 13.2 and 13.3. Volume per hectare was therefore calculated as:

$$V_{ha} = V_{S\phi} * S_0 * \phi \quad (13.4)$$

where:

- S_0 is the initial number of stems per hectare (S_0 = 1000);
- ϕ is survival; and
- V_s is the volume per tree for a stocking of S_ϕ trees per hectare when survival is ϕ, given by Equations 13.1, 13.2 and 13.3.

The second scenario assumed that mortality is 'patchy' throughout the stand. This can occur, for example, due to severe frosting in a hollow within the stand or localised pest attacks. The difference with this second scenario from the first, is that the spacing between the survivors is kept equal to the fully stocked stand. That is, there is no stocking effect on individual tree volume, only yield per hectare is affected. Volume per hectare in this case was calculated as:

$$V_{ha} = V_{S=1000} * S_0 * \phi \qquad (13.5)$$

where:

- S_0 is the initial number of stems per hectare;
- is survival; and
- $V_{s=1000}$ is the volume per tree for a stocking of 1000 trees per hectare.

The breeding objective considered here (denoted V_{ha}) is simply the volume production per hectare at a given age t. The economic weights for each trait are defined as the changes in V_{ha} per unit change in V_s and ϕ.

13.2.3 Selection Strategies

Selection criteria considered in this paper include volume per tree alone, and a combination of volume per tree and survival. The selection index considered refers to forward selection combining individual and family information for growth (volume per tree) and/or family information for survival:

$$I = b_1 X_{(Vol/Tree)} + b_2 F_{(Vol/Tree)} + b_3 F_{(Survival)} \qquad (13.6)$$

where:

- $X_{(i)}$ and $F_{(i)}$ represent individual and family information, assumed to be based on an initial sample size of 30 individuals from a half-sib family.

Selection index based on progeny or backward selection, combining offspring information on growth and/or survival, were also tested but produced results similar to those from forward index selection, and the results are not shown here.

Index coefficients (b) and genetic gains (ΔV_{ha}) for each index were calculated using the RESI program (Cotterill and Dean 1990, Chapter 11), and a selection intensity of 1:100 (i=2.665).

13.2.4 Genetic and Phenotypic Parameters

The genetic and phenotypic parameters used in this study are given in Table 3.1. Heritability for tree volume and survival was considered constant, 0.20 and 0.30 respectively, but three correlations between the two traits were considered: r_g = -0.5, 0 and +0.5. A complication that arises when dealing with survival is that the individual phenotypic values are binomial, hence variances are dependent on the mean frequency. A common assumption is to assume a continuous underlying distribution of genotypes (McGuirk, 1989), in which case, the heritabilities for survival would vary on the phenotypic scale according to:

$$h_{0/1}^2 = h_L^2 * \frac{z^2}{p(1-p)} \qquad (13.7)$$

where:

- $h_{0/1}^2$ is the heritability on the observed binomial scale;
- h_L^2 is the heritability on the underlying scale (assumed to be 0.30 in this study);
- p is the incidence of survival in the unimproved population (covering the range 0.4 to 1.0); and
- z is the height of the ordinate at the threshold corresponding to the underlying distribution of survival.

In the current study, phenotypic correlations were estimated from:

$$r_L \cong r_G * h_{L1} * h_{L2} \qquad (13.8)$$

where:

- r_L is the phenotypic correlation between tree growth and survival on the underlying scale;
- r_G is the genetic correlation between the two traits; and
- h_{L1} and h_{L2} are square-roots of the heritabilites for tree growth and survival on the underlying scale, respectively.

This assumes no environmental covariances between the two traits. Phenotypic correlations for survival, however, also vary on the phenotypic scale (Olausson and Rönningen, 1975) according to:

$$r_{0/1} = r_L \left\{ \frac{z_A^2}{p_A(1-p_A)} \right\}^{1/2} \quad (13.9)$$

where:

- trait A is assumed to be survival;
- $r_{0/1}$ and r_L are the phenotypic correlations calculated on the binomial and underlying liability scale respectively;
- p_A is the incidence of survival; and
- z is the height of the threshold on the underlying scale for trait A (survival).

13.2.5 Efficiency of Selection

The relative efficiency, in terms of gains in the breeding objective, of selecting on an index based solely on volume per tree (index 1) versus an index combining volume per tree and survival (index 2), was calculated as:

$$E = \frac{\Delta V_1}{\Delta V_2} \quad (13.10)$$

where:

- ΔV_1 and ΔV_2 are the gains in volume per hectare from indices 1 and 2 respectively.

Table 13.1- Genetic and phenotypic parameters for growth (in dm^3/tree) and survival (in percentage units), where σ^2_p is the phenotypic variance, h^2 is the narrow sense heritability and $r_{p(0/1)}$ is the phenotypic correlation between growth and survival on the binomial scale, when genetic correlations are -0.5, 0, and +0.5 respectively.

Incidence of	σ^2_p		h^2		$r_{p(0/1)}$		
Survival	Vol/Tree	Survival	Vol/Tree	Survival	r_g= -0.5	r_g= 0	r_g= +0.5
(p)	(dm^3)	(%)	(dm^3)	(%)*			
0.90	100	9.00	0.20	0.1061	-0.0781	0	0.0781
0.80	100	16.00	0.20	0.1519	-0.0935	0	0.0935
0.70	100	21.00	0.20	0.1785	-0.1013	0	0.1013
0.60	100	24.00	0.20	0.1928	-0.1053	0	0.1053
0.50	100	25.00	0.20	0.1973	-0.1065	0	0.1065
0.40	100	24.00	0.20	0.1928	-0.1053	0	0.1053

* Assuming an underlying heritability of 0.30

13.2.6 Desired Gain Indices

To examine the impact of allowing increased weightings and selection pressure for survival, when stocking in deployed populations will be 100%, the method of desired gains or restricted indices (Pesek and Baker 1969, Cotterill and Jackson 1985) was used. Although there are criticisms on the use of restricted indices (Gibson and Kennedy 1990), the method was considered a useful tool in this context, because the cost, hence importance, of mortality may vary widely in stands from different regions. The scenario used was a desired gain in survival of 30%, when in fact, all trees in the deployed plantation survive. The selection index (index2) still sought to improve survival up to the additional 30% at a cost in volume. Following the approach of Brascamp (1984), Woolaston (1994), and Woolaston and Jarvis (1995), gains in volume/tree were allowed to be maintained at a maximum (i.e. gains in volume/tree given an economic weight for survival of zero), while changes in survival were restricted. This allowed the opportunity cost of including survival in a selection index, given a stand is already fully stocked, to be determined in terms of gain foregone in volume/tree.

13.3 Results

As expected with this model, volume per hectare drops as mortality increases. The drop is linear (proportional to the number of stems per hectare) if mortality is patchy, but in the case of dispersed mortality there is compensatory growth from survivors (Figure 13.1), and hence the drop in volume per hectare is attenuated as these survivors compensate in size.

13.3.1 Economic Weights

Table 13.2 presents the economic weights, given as marginal changes in volume per hectare (m^3/ha) resulting from changes in one unit of volume/tree or one percentage point in survival, and their relative counterparts, that is, the importance of improving one phenotypic standard deviation for each trait. Survival is, in relative terms, a more important trait than volume per tree to maximise volume per hectare, except when survival is above 90%. This is more evident in the case of 'patchy' mortality where, for high levels of mortality (say 50%), survival is up to 6.5 times more important than tree volume. When mortality is regularly dispersed throughout the stand, the economic importance of survival, as expected, is attenuated due to surviving trees compensating in size for the loss of their neighbours. In both scenarios survival was shown to be a major trait in

maximising volume per hectare, with its importance increasing as mortality within the stand increases.

Figure 13.1- Volume per hectare as a function of stocking as predicted by Equations 13.1 to 13.3 (from Bredenkamp, 1987), where (————) represents dispersed mortality and (- - - - -) represents patchy mortality at 10 years.

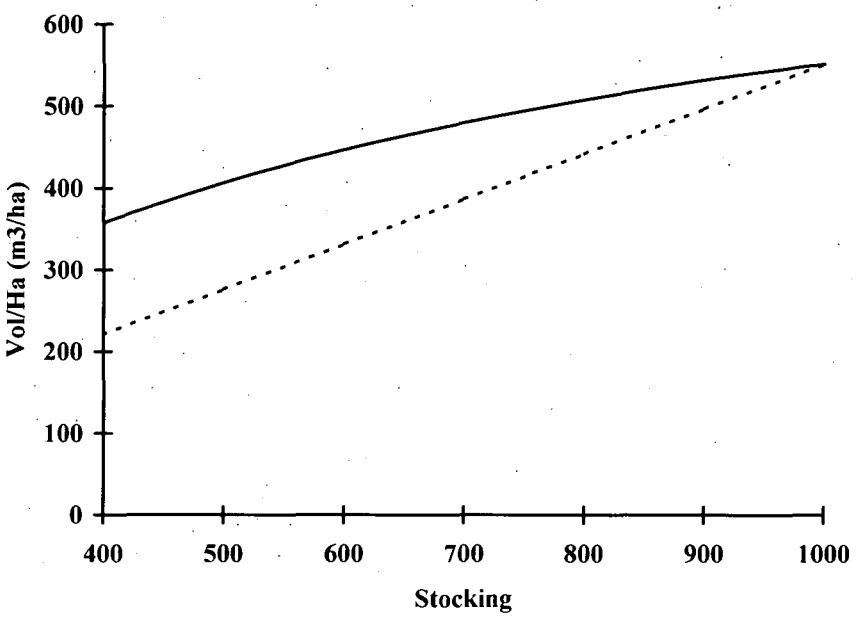


Table 13.2- Absolute and relative economic weights for tree volume and survival for dispersed and patchy mortality (values represent gains in volume per hectare (m^3/ha), and for one unit of phenotypic standard deviation for absolute weights and relative weights, respectively.

Incidence	Dispersed Mortality				Patchy Mortality			
	Absolute Weights		Relative Weights		Absolute Weights		Relative Weights	
(p)	Vol/Tree*	Survival	Vol/Tree	Survival	Vol/Tree*	Survival	Vol/Tree	Survival
0.90	0.90	2.19	90	65.7	0.87	5.52	87	165.6
0.80	0.80	2.57	80	102.8	0.77	5.52	77	220.8
0.75	0.75	2.79	75	119.7	0.73	5.52	73	236.9
0.70	0.70	3.03	70	138.8	0.68	5.53	68	253.4
0.65	0.65	3.31	65	156.9	0.63	5.53	63	262.2
0.60	0.60	3.61	60	176.9	0.58	5.53	58	270.9
0.50	0.50	4.37	50	218.5	0.49	5.53	49	276.5
0.40	0.40	5.35	40	262.1	0.40	5.53	40	270.9

* Assuming: $\sigma^2_{Vol/Tree} = 100dm^3$

** Assuming: $\sigma^2_{Survival} = p(1-p)$

13.3.2 Gains in the Breeding Objective

Expected gains in the breeding objective (V_{ha}), for the two selection indices (and across a range of survival from 40% to 100%) are detailed in Figure 13.2 for dispersed mortality, and Figure 13.3 for patchy mortality. Heritability for growth appears to be consistently moderate for a number of species and the $h^2 = 0.20$ used in this study should be a reasonable approximation. Much less is known on the inheritance of survival and the genetic correlations between early survival and growth. In *E. globulus*, Chambers *et al.* (1996) found the heritability of survival to range between 0.19 and 0.57 depending on the environmental causes associated, and a genetic correlation between early survival and growth to range between 0.08 and 0.81 with an average of 0.50 across a range of sites under different environmental conditions. In another study, Dutkowski (1995) found a consistent negative correlation across four trials in Western Australia, with values ranging between -0.43 and -0.05. This disparity of values, is certainly a consequence of differences in the primary causes of mortality across trials and biases in the estimates themselves. To cover the range of values found in the literature, three levels of genetic correlation were used, namely -0.5, 0, and +0.5.

It can be seen from Figures 13.2 and 13.3, that selection combining volume per tree and survival (index 2) results in substantially higher gains than selection based on volume per tree alone (index 1). The importance of including survival as a selection trait increased as mortality within the stand increased. Gains in survival were greatest in all cases when the mortality was 50%, which is the level at which underlying phenotypic variation is greatest. At higher incidences (>90%), the variation in survival was negligible and predicted gains in volume per hectare from index 2 were comparable to those predicted from index 1. Survival is an even more important trait when mortality within the stand is patchy, mainly at higher survival levels. It is apparent in Figure 3.3, that when survival was 50% for example, gains in volume per hectare had a maximum. Given an initial value of 50% and $r_g = 0$, survival can be improved to 78% from forward selection after only one cycle of breeding (data not shown) using index 2. Gains in volume per hectare at low survival is therefore mostly due to an increase in number of trees alive per hectare.

Figure 13.2- Expected gains in volume per hectare from forward selections (- - - - - -) based on volume per tree only (Index 1), and forward selections (————) based on a combined selection index of volume per tree and survival (Index 2). Three different correlation scenarios are assumed, and mortality is dispersed.

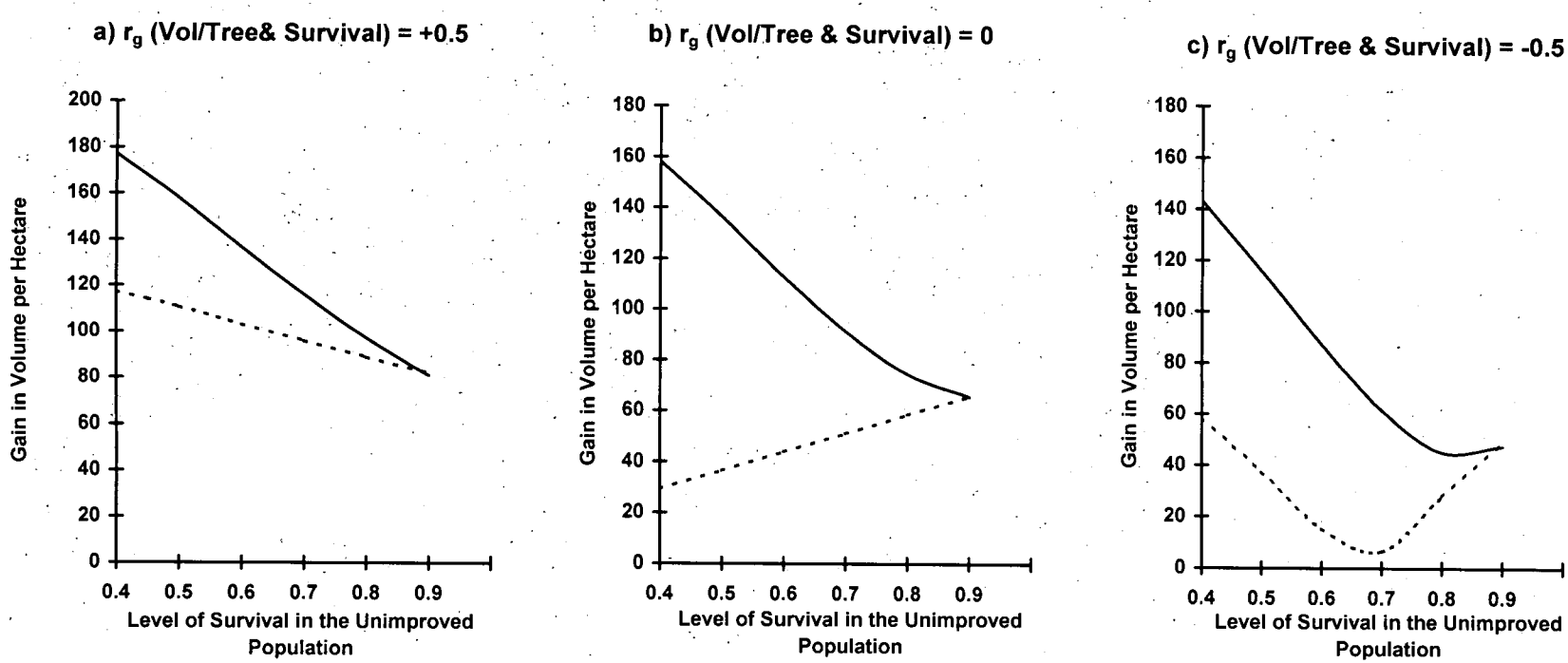


Figure 13.3- Expected gains in volume per hectare from forward selections (- - - - -) based on volume per tree only (Index 1), and forward selections (———) based on a combined selection index of volume per tree and survival (Index 2). Three different correlation scenarios are assumed, and mortality is patchy.

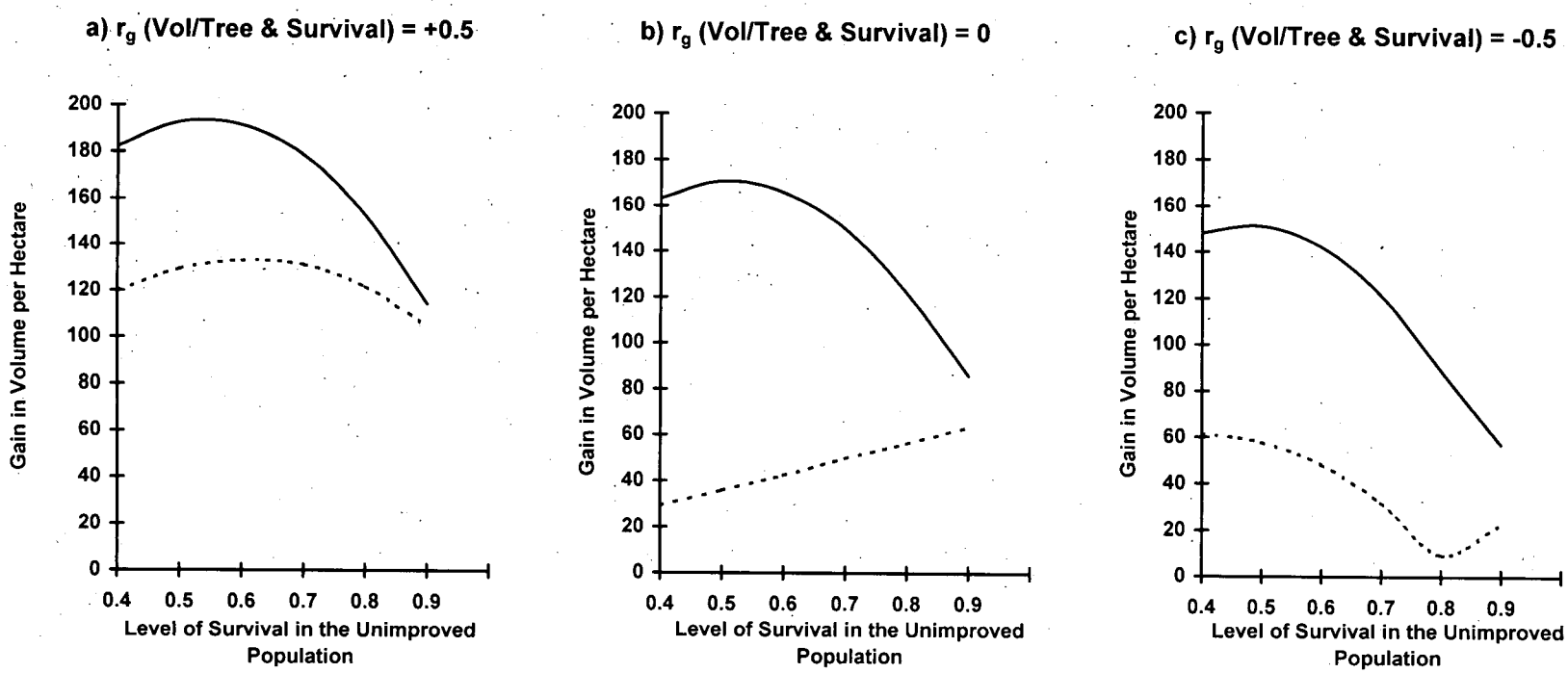
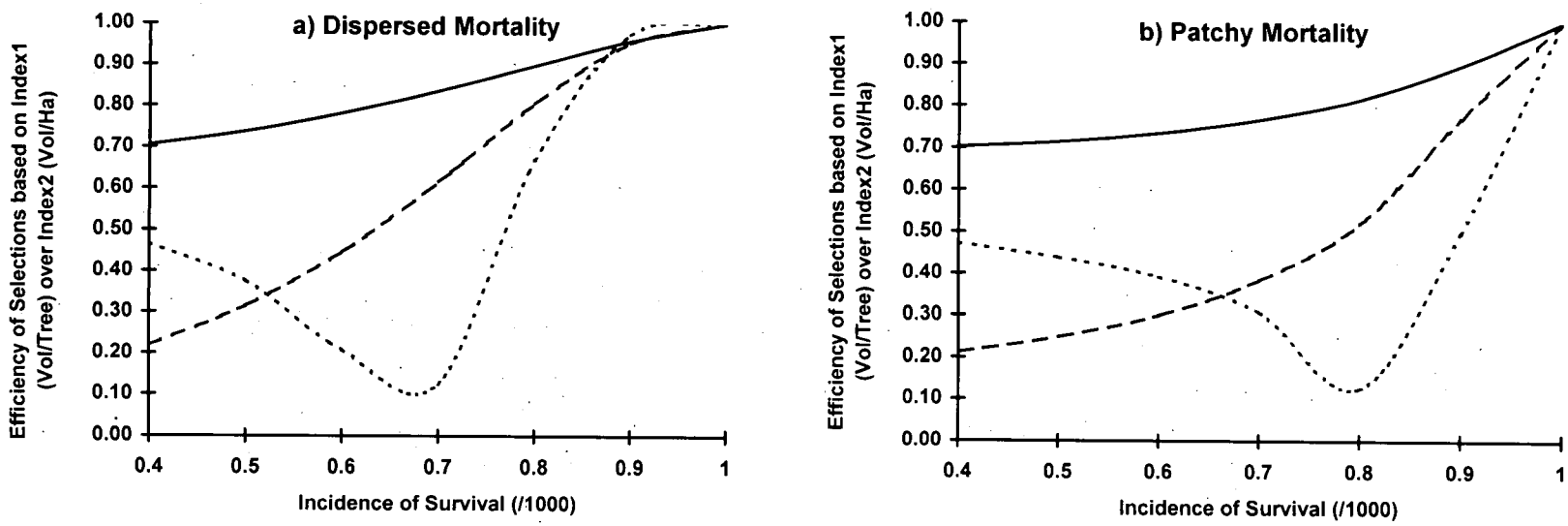


Figure 13.4- Efficiency of Selections based on Index 1 (volume/tree) as opposed to Index 2 (volume/hectare) versus Incidence of Survival when mortality is (a) dispersed or (b) patchy, where r_g is -0.5 (·····), 0 (- - - - -) and +0.5 (———).



13.3.3 Efficiency of Including Survival as a Selection Trait

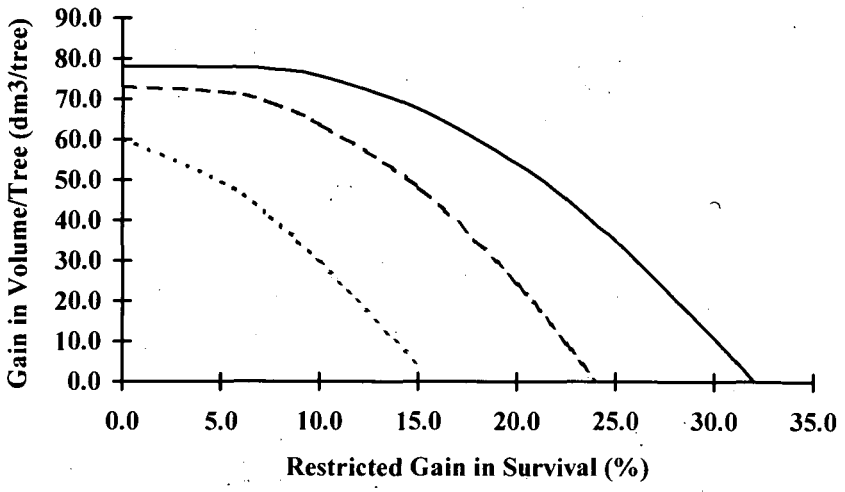
The importance of incorporating survival as a trait in the breeding objective is considerable (Figure 13.4), particularly as the genetic correlation between growth and survival goes from positive to negative.

Efficiency, that is gains from an index including only volume per tree compared with gains combining volume per tree and survival were lowest (E = 10%) when mortality was dispersed, survival was 68% and it had a negative correlation with volume per tree (Figure 3.4a). Below the 68% level, efficiencies improve due to a negative selection on volume per tree (i.e. *b* coefficients being negative). In other words, survival at high mortality rates becomes such an important trait in the breeding objective (see Table 3.2), that the index uses the information on volume (by choosing the smaller trees) as an indirect means to improve survival. This trend was also apparent for the patchy mortality scenario (Figure 3.4b), where minimum efficiency was achieved at 78%. Although no dramatic shift in gains for each individual trait occurred when positive and zero correlations between the two traits existed, efficiency steadily decreased with increasing mortality. Overall, indices only using volume per tree were considerably inefficient (E between 0.2 and 0.5) unless the genetic correlation between volume per tree and survival was strong and positive. Efficiencies were lower when selection was based on progeny performance compared with co-lateral relatives (data not shown), but the trends remained the same for backward and forward selection schemes.

13.3.4 Desired Gain Indices

A characteristic of survival as a trait, is that its opportunity cost, and hence the economic weights, may vary widely depending on the geographic location of the stand and the effectiveness of silviculture to maintain stocking at an adequate level. This variation in the importance of including survival as a selection trait, makes it difficult to derive a universally applicable weighting for this trait. A method to handle such uncertainty is to use desired gain indices, as discussed by Woolaston and Jarvis (1995). This is illustrated in Figure 13.5, in which selection weighted survival at various levels, but the deployed population had a 0% mortality. It is apparent from Figure 13.5, that some weight can be given to survival without greatly compromising gains in volume per tree, even when survival in the deployed population remained at 100%. Naturally, this inference depends on the accuracy of assumptions about genetic parameters, and further supporting evidence for the assumptions used in this study would increase reliability.

Figure 13.5- Impact on volume/tree, when survival is included in a selection index to improve volume per hectare and the stand is already fully stocked, where r_g is -0.5 (·····), 0 (- - - - -) and +0.5 (———)



It can also be seen from Figure 13.5, that the opportunity cost of including survival increases considerably when genetic correlations are adverse between survival and volume per tree. When the correlation between the two selection traits is positive, volume per tree is not dramatically affected until desired gains in survival are greater than around 15%. However gains in volume per tree remain positive in this case until beyond 30%, which is the maximum improvement that would be made in any case, with the assumption used here of an expected 70% survival. When $r_g = 0$, the cost of survival increases steadily (shown by the steady decrease in gains for volume per tree in Figure 3.5), but does not greatly compromise potential gains in volume per tree until desired gains for survival are around 10%. Only when the genetic correlation between the traits is strongly negative, the cost of including survival may be large, unless improvements are restricted to only 3 or 4 %.

13.4 Discussion

Survival, as a trait, can be determined by a number of factors, but its impact on the productivity per hectare is, whatever the cause, substantial. The large economic weights for survival in Table 13.2 suggest that traits such as tolerance to ground frost, drought or specific pests, in areas where significant mortality due to one of these causes is likely to occur, may be more important to breed for than volume per tree. The diversity of conditions across forest plantations is an important issue however, because whilst volume per tree is constantly important in maximising productivity per hectare, survival, or each type of survival ability is only an issue if

some particular environmental deficiency or pest occurs. The impact of mortality due to drought, for example, may be associated with particular landscapes or soil types within those landscapes (Dutkowski 1995), and future planting can channel plantations away from the susceptible areas, or the causes overcome by irrigation for example. When dealing with aspects of sustainability in short rotation tree species, the selection on survival will definitely become an even more important issue and possibly the dominant criterion in many cases. The establishment of plantation programs requires good survival of the species and families being deployed, which may become an issue for such species as *Eucalyptus* which is a rather site sensitive genus.

A potential problem with the interpretation of the results presented in this study is therefore that the factors conditioning survival may change amongst trees or trials. The success of increasing gains in volume per hectare by including survival in a selection index depends ultimately then, on survival being caused by a few major factors and on our ability to identify them within a given stand. In its simplest case, the cause of mortality within the plantation or progeny trial is assumed to be consistent across all replicates and blocks, and amenable to improvements by genetic means. It may be more difficult to improve survival by index selection from a single progeny trial where mortality is restricted to only a few blocks, or to include data from trials where mortality was a random process as may occur after a storm, where the underlying genetic variation for survival may be slim or nonexistent. Changes in the cause of mortality with age may also occur, for example due to frost in the first year, to drought or disease in later years. When comparing survival across different sites, Chambers *et al.* (1996) however, found encouraging results that genes leading to higher survival may be prevalent in a range of environments, with genetic correlations for survival at different sites ranging between 0.14 and 0.92.

The relationship between survival (stocking) and wood density or pulp yield is the topic of some conjecture in different species (Zobel 1992). In the case of eucalypts however, Tomé *et al.* (1995) and Pereira *et al.* (1995) have reported negligible effects of spacing (and thus survival) on wood density and fibre characteristics. This being the case, the results presented here can be safely extrapolated to fibre production (for instance tonnes of pulp per hectare). This will have important consequences for the establishment of selection programs for pulpwood and pulp and paper production systems, for which short rotation plantations are primarily targeting, in areas where lower survival is likely to occur.

It should be noted that the gains described in both traits in the breeding objective (volume/tree and survival) were assumed independent. This implies that relative gains in volume per tree remain consistent across a range of survival, and hence

that the variation in volume per tree does not change across this range. In a real-life situation however, gains in volume per tree may actually be larger with lower survival. Hence, the method used in this study (i.e. the assumption of equality of variances and change in mean values only) may underestimate the gains in volume per tree and ultimately volume per hectare in stands of low survival. A solution would be to define a non-linear selection index function which would allow gains in volume per tree to be dependent on the gains made in survival. Since only those stands of very low survival would be affected by such bias, the concept of non-linear selection indices was ignored in this study. The use of an empirical growth function relating individual tree growth and spacing to predict the economic importance of improving early survival is certainly a reasonable approach to estimate the relative importance to breeding of tree size and survival. This is providing the function describes the growth of trees under various spacings well, but may lead to incorrect economic weights if relationships are not correct. The authors believe that further work needs to be done in this area. Nevertheless, this paper provides a simple framework to guide breeders on how to weight more objectively traits such as frost, drought or pest tolerance with typical key traits such as volume, stem straightness and wood characteristics in breeding and selection decisions.

13.5 Conclusion

The results clearly showed that survival is a very important selection trait when aiming to maximise productivity per hectare. The importance of survival increases with increasing mortality within a stand and adverse genetic correlations between growth per tree and survival. Providing the causes of mortality can be identified, it is recommended that survival ability for such causes be incorporated into selection programs. This would present little problem, considering the ease with which family information for survival may be incorporated into the breeding objective.

Chapter 14
The genetic control of flowering precocity and the implications to breeding
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Chapter 15

General Discussion and Conclusions

The work described in this thesis has sought to investigate the question: *what defines a good tree?* Historically "*good*" trees have been selected as trees with good growth and good form. However radiata pine is grown in south-eastern Australia for the production of a number of solid wood and paper products, and a "*good*" tree should be a tree which is optimum for the production of these products (i.e. a tree which maximises overall enterprise profit). The classical definition of 'aggregate genotype' by Hazel (1943) provides a formal framework to allow a breeding objective to be defined, and following the procedure of Ponzoni and Newman (1989), is a convenient means to answer the question posed. The breeding objective is described by a profit function as discussed in Chapter 6, that takes genetic values as input and produces profit as outcome. The traits included in the profit function should relate as directly as possible to all sources of income and costs (Goddard 1998). It seems to be the current consensus to base the profit function on a bioeconomic model with the estimation of covariances used in choosing selection criteria (Goddard 1998). In addition, for a vertically integrated enterprise, a profit function with optimised management and that can not gain by increasing the scale of the enterprise is widely applicable. Goddard (1998) suggests that an attempt should be made to account for all costs and to assign them correctly to the variables that determine them in the long term. This procedure allows a check to be made that long term profit is close to zero (see Chapter 6).

15.1 Some final comments on the definition of breeding objectives

15.1.1 Uncertainty of Objectives

Unexpected changes in future prices and costs lead to the profit function changing with time and ultimately to uncertainty in breeding objectives. The concept of risk loading applied to the 'real' interest rate as discussed in Chapter 6 is, in part, justified due to this uncertainty. Miller and Pearson (1979) and Goddard (1998) postulate that this uncertainty is a major reason why producers have not traditionally used formally defined breeding objectives and corresponding selection indices.

One solution for tree breeders or national industries may be to keep several different 'groups' or 'lines' which are selected for different objectives as a fall-back position against changes in future objectives. Smith (1985) concluded that this is an economically justifiable position, assuming that by keeping extra lines would decrease the risk loading in the discount rate. Because breeding programs have high ratios of income to costs, a small reduction in the discount rate applied to long term income can justify multiplying the cost by the number of lines (Smith 1985). Goddard (1998) however discusses that the risk caused by uncertainty of future prices should not be overemphasised. Indeed, the value of genetic gain is fairly insensitive to small errors in economic weights (Smith 1983).

15.1.2 Multiple Objectives

It is often the case in forestry, that breeders seek to sell seedstock to more than one market. Indeed the breeding objective defined in this thesis, must provide wood which on one hand is acceptable for pulping, and on the other is good for the production of solid wood products. Shelbourne *et al.* (1997) however concluded that there is a high degree of commonality in requirements of these different forest products, both in breeding objective traits and in corresponding selection criteria, which is fortunate for tree breeders. Howarth *et al.* (1997) present three strategies to cope with the concept of multiple breeding objectives and discuss the advantages or disadvantages of each. Firstly, the breeder may specialise in one particular market, or secondly split the forest plantations into sub-lines that specialise in the different markets, or finally select for an objective that is the average of the different markets. Shelbourne *et al.* (1997) have proposed the second approach for the

production of different grades of solid wood products; using two main breeding objective definitions called "general purpose lumber" and "appearance lumber".

15.1.3 Profit as a Trait

If profit could be recorded on individual trees, as are other traits, then the need to define a profit function would be circumvented (Goddard 1998). The breeding objective would be the single trait 'profit' and the selection indices (e.g. BLUP) would merely require estimates of genetic parameters involving this extra trait. In principle, all income and costs associated with each tree need to be recorded and profit calculated. However, in practice, profit is usually calculated from records of timber and paper sale and other traits by a rule of the form: $PROFIT = f(x)$, where x are the phenotypic trait values. This phenotypic profit function is equivalent to the genetic profit function presented previously in Chapter 6 (i.e. $PROFIT = f(g)$) and so Goddard (1998) concludes that in the majority of cases, the need to define a profit function is not really avoided. If $f(x)$ is non-linear, then the covariances between profit and traits in x will change as the mean changes. As such, the genetic covariances involving *PROFIT* must be continually re-estimated, which is a disadvantage to the use of the trait profit as the objective. Another major disadvantage identified by Goddard (1998) is that, if economic weights change, the definition of the trait profit also changes. However, if there are complex relationships between the traits in x, then calculating profit directly may be more robust than using a complex bioeconomic model. Visscher and Goddard (1995) estimated genetic parameters for a partial definition of profit and suggested that profit has the potential to be included in a multiple-trait BLUP with more conventional traits. A partial definition of profit that depends on only a few related prices would minimise the problem of the definition of the trait changing as prices change.

15.1.4 Broader Objectives

The breeding objective has been defined in the current chapter based on genetic values, not breeding values. Thus non-additive genetic changes, such as inbreeding depression, are automatically part of the objective. Due to the fact that the breeding objective is about the value of genotypes at some period into the future, factors such as loss of genetic variance from inbreeding (which decrease the rate of genetic gain) are also part of the objective (Goddard 1998). Although it may be appropriate to define these types of effects as part of a breeding objective, this definition greatly complicates methods that calculate optimum selection policies

such as the traditional selection index (Goddard 1998). A number of authors including Goddard (1990), Wray and Goddard (1994) and Brisbane and Gibson (1995) show how the effects of inbreeding might be included when selection decisions are being made, however a discussion of this is beyond the scope of this thesis.

The objective may also include the variance of future mean genetic value if risk avoidance is part of the tree breeder's aim. Selection procedures that include risk avoidance are discussed by Schneeberger *et al.* (1982) and Wooliams and Meuwissen (1993).

15.2 Thermomechanical pulping studies

From a review of the literature, it would seem that no single wood property influences the amount of energy required during refining, and that tracheid properties seem equally important (Chapter 2). Basic density seems to be a good indicator, but not predictor of specific energy. As such, components of wood density (cell wall and fibre size and fibre tangential diameter) which also influence the stiffness of both solid wood and individual wood fibres (Nyakuengama 1997) may be more important in predicting energy requirements of wood than basic density, a solid wood property. A number of physical wood properties have also been demonstrated to directly determine suitability for paper production (Chapter 2). However, the effect of most of these properties is vague due to the inter-relationships between them. For example, fibre coarseness seems to depend on both fibre size and fibre wall thickness (Nyakuengama 1997), which in turn affect fibre bonding, strength and the optical properties of the paper sheet.

From a pulping and handsheet study undertaken in Chapter 4, the specific energy consumed during refining, and the tear index and tensile strength of a pulp handsheet were all shown to be best explained by a combination of the tracheid length and basic density of wood (Table 4.4). Handsheet brightness and opacity were shown to be best explained by wood brightness and tracheid coarseness respectively (Table 4.4). However, these studies were based on data derived from a pilot laboratory scale study and may need verification on a larger mill scale. Of equal importance were a number of functions developed relating each of these pulp handsheet traits to the costs of relevant production commodities (Table 4.2). In the majority of cases, these were based on previously unpublished work carried out at Fletcher Challenge Paper's Boyer Mill.

It is a common practice to predict the properties of a two dimensional paper sheet from laboratory handsheet assessments measured in a single dimension (Smook 1992). However, paper has a definite "grain" caused by the greater orientation of fibres in the machine direction of the paper machine and by the stresses imposed during pressing and drying. The directionality of paper must be taken into account in measuring physical properties and for such strength measurements as tear, tensile and burst, strips of paper are cut in both directions for testing. However, the impact of directionality on optical properties is considered minimal (McKenzie 1994). However, as discussed by Smook (1992) the machine direction (MD) and cross direction (CD) strengths of a machine-made paper are closely related to the strength of a randomly orientated sheet made from the same stock furnish. This is the basis on which pulp handsheet assessments conducted in the laboratory provide a reasonable indication of the physical strength properties of a sheet of paper produced on a mill scale paper machine (Smook 1992).

The most important traits for breeding to reduce the cost of thermomechanical pulping and high brightness newsprint production were wood density, wood brightness and tracheid length (Chapter 4). An increase in one unit of each trait (Table 4.5) reduced the costs of thermomechanical pulping and high brightness newsprint production by $17, $16 and $15 per oven dry tonne of TMP produced, in wood density, wood brightness and tracheid length respectively. This compares to an analogous study in Chapter 5, where the breeding objective was to reduce the cost of low-grade newsprint production from thermomechanical pulp. In this case, as expected due to the cheaper method of bleaching assumed, wood brightness appeared to be much less important than described by Chapter 4. In both studies, the impact of tracheid coarseness of reducing costs was small relative to the impact of the other traits.

Many papermakers rely on the addition of relatively expensive kraft pulp to improve the flaw-carrying ability, and hence the runnability (or paper strength) of the newsprint sheet (Mohlin 1984). Nevertheless, due to its expensive nature, there is always a desire to minimise the amount added. The interaction between TMP and kraft pulp is discussed very little in the literature, even though it is a well accepted fact that paper properties can not be predicted by assuming a linear weight-proportion dependence of the properties of the blends on those original pulps (Mohlin and Wennberg 1984). The results obtained in Chapter 3 indicate that gains in pulp handsheet strength due to the addition of kraft pulp do not manifest until a minimum level of between 5 and 8% of kraft pulp is added to the TMP furnish. This has important implications for pulp mills seeking to achieve gains in the flaw-carrying capability of newsprint sheets by adding very small amounts of kraft pulp.

15.3 Production system and economic weights

The enterprise over which profit should be maximised was defined in Chapter 7 as a system which establishes, clearfalls, and processes unpruned radiata pine to structural grade flitch and high brightness newsprint from thermomechanical pulp over a plantation area of 3000 hectares. As modeled, this enterprise was profitable (Table 7.6) with net profits being 19.9% of net costs. The majority of wood volume is assumed to be utilised to produce newsprint (77% by volume) with only 23% used to produce rough green flitch. The income derived from producing newsprint exceeded the income derived from the production of flitch by around ten times, however the flitch production line was estimated to be much more profitable (*Profitability Index* 32.9%) compared to the newsprint production line (*Profitability Index* 18.8%). However, the profitability of the flitch component of the business is dependent upon the existence of the newsprint component to utilise sub-flitch grade logs.

The traits selected as affecting the enterprise profitability (i.e. the breeding objective traits) were: mean annual increment (*MAI*), bark volume (*BRK*), branch size (*BIX*), stem sweep (*SWE*), stem taper (*TAP*), basic density (*DEN*), basic working strength of timber (*BWS*), mean tracheid length (*LEN*), tracheid coarseness (*CRS*) and wood brightness (*BRG*). The breeding objective was defined as a linear combination of the derived economic weights for each of these traits presented in Table 8.20:

$$H_{PI} = 0.33(\Delta MAI) - 0.09(\Delta BRK) - 0.85(\Delta BIX) - 0.14(\Delta SWE) - 0.14(\Delta TAP) + 0.08(\Delta DEN) + 0.76(\Delta BWS) + 5.87(\Delta LEN) - 2.05(\Delta CRS) + 0.32(\Delta BRG)$$

where:

- H_{PI} is the aggregate genotypic breeding value for profitability index and *MAI, BRK, BIX, SWE, TAP, DEN, BWS, LEN, CRS, BRG* are the estimated breeding values (as deviations from the population mean) of biological traits of the genotype.

However, the economic weights for each trait are difficult to compare because they are, by definition, the economic advantage associated with a unit change in each trait, which each have differing units. The value of a 10% increase in each trait (Tables 8.2 to 8.19) begins to put the value of a trait improvement into perspective. Increasing basic density by 10% had the greatest effect on the defined production system and will increase the overall profitability index by 3.32% (Chapter 8), which corresponds to a present value (defined at plantation establishment) of predicted gain of $9.3M. A 10% increase in wood brightness and tracheid length resulted in

moderate increases in overall enterprise profitability indices of 1.61% and 1.41% respectively. Other traits examined, with less impact on the defined production enterprise and their respective profitability index changes were: bark percentage -0.07%, branch index -0.43%, stem sweep –0.04%, stem taper –0.07%, and tracheid coarseness –0.09% (Chapter 8). However, the values of a 10% increase in each trait, while more indicative of the value of trait improvement than the economic weights listed above, do not account for differences in the exploitable genetic variation between traits. For example, there is considerably more exploitable genetic variation in growth rate (e.g. Carson 1991) than there appears to be in most wood property traits such as basic density and tracheid coarseness (Nyakuengama *et al.* 1997. Shelbourne *et al.* 1997, Chapter 9). Similarly, these estimates do not account for the genetic correlations between traits.

15.3.1 Sensitivity analysis

The input parameter to which *Profitability Index* is most sensitive is the value of newsprint across harvesting operations (abbreviated *IRNEWS* in Chapters 7 and 8). Changing *IRNEWS* by the allowable sensitivity range (±20%) changes *Profitability Index* by 0.66%. The economic value of improving basic density (the trait with the greatest impact on the production enterprise as defined by a 10% increase, Chapter 8) was also shown to be most sensitive to the assumed newsprint value across harvesting operations, underlining this parameter as a key driver in overall enterprise profitability. However the assumed newsprint value ($960 per OD tonne newsprint) is in the realistic range for the prices paid in Australia for such a commodity. A number of model parameters were shown to have an affect on enterprise profitability (Table 7.8), however the impact of these parameters was relatively small and assumed to have a negligible economic impact.

An important parameter determining the economic value of basic density and tracheid length was the intercept term in a model relating specific energy consumption to each of these breeding objective traits (Eqn. 8.14). The data from which this relationship was derived was based on a pilot laboratory scale study and may need verification on a larger mill scale. Another model parameter which describes a linear relationship between the amount of peroxide required to achieve a specific increase in pulp handsheet brightness, and termed "*PER CONSTANT*" in Tables 7.8 and 8.22 may also require further verification. There is a large amount of evidence to suggest that this relationship is anything but linear except for extremely narrow regions of the response curve (George Ionides, *pers. comm.*). Table 4.2 suggests however, that this relationship is stable for changes in peroxide

of the range of 2% to 7.1%. Future work, with the possibility of improving the model sophistication using non-linear methods should be examined.

Discount rate also rated among the ten most sensitive input parameters, but this was based upon the allowable variation in discount rate of ±20%, a range in discount rate of 4% to 6%. As discussed in Chapter 6, the choice of discount rate is dependent upon factors such as risk. However, Klemperer *et al.* (1994) have suggested that the appropriate discount rate might vary from 3% to 10%.

The assumptions used in the current analysis have different degrees of certainty, but all were arbitrarily allowed to vary the same relative amount in the sensitivity analysis. The results of this sensitivity analysis reflect the constraints imposed upon input parameters by this arbitrary variance, but were used simply to indicate the first parameters which needed clarifying in subsequent modeling efforts. Refinement of the model inputs to any further extent is beyond the scope of this work as actual production system inputs are generally considered to be commercially sensitive.

15.3.2 The value of an increase in growth rate (MAI)

The benefit of increasing Mean Annual Increment (*MAI*) was assumed to be derived from an increase in volume produced per hectare without appreciably changing growing costs. Increasing *MAI* was assumed not to influence any component of processing economics – it simply reduced growing costs relative to processing costs. This might be achieved silviculturally by establishment stocking being increased in direct proportion with *MAI* – that is, a 10% increase in *MAI* requires a 10% increase in establishment stocking (with a factored increase in establishment costs – Eqn. 22). Rotation length is unchanged so the trees grow to the same size as unimproved stock, but there are 10% more trees per hectare at harvests.

This, however, is probably not the way in which growers have chosen to exploit faster growing genotypes. Growers have probably chosen to maintain or reduce stocking and to harvest their forest earlier as grown trees reach a desirable size in a shorter time. However, this may result in confounding changes to the overall enterprise economics. Younger trees may have lower density (Uprichard 1980), lower kraft pulp yield (after Uprichard and Lloyd 1980), reduced timber strength and stiffness (Kennedy 1995), and reduced newsprint strength properties. These changes could have occurred in the absence of genetic improvement by planting unimproved material at a wider spacing and reducing rotation length. Thus, the economic advantage of increasing *MAI* would be exaggerated if analysis assumed either shorter rotations or the production of bigger trees over the same rotation.

The assumption that increasing growth allows the grower to produce proportionally more roundwood of the same "type" is a simplifying assumption, that aims to minimise the confounded effects of silvicultural changes.

Ladd and Gibson (1978) and Amer *et al.* (1994) argue that the enterprise may need to be re-optimised as a result of genetic improvement, and that the economic value of improvement must account for any resulting change in the enterprise's operations. In the context of forestry and forest products, reoptimisation may involve changing rotation length or silvicultural management of growing plantations, and further work in the area of breeding objectives should extend the multi-trait modeling process to examine the re-optimisation of systems of forest management and utilisation.

15.4 Prediction of economic gain from multi-trait selection

Gains from family-mean and combined selection (individual-tree assessment with selection based upon an index of individual and family-mean values) were estimated for a range of selection options. Maximum gain (Table 11.5) was calculated assuming all traits were assessed on an individual-tree basis. Of importance was the fact that combined selection solely on growth captured only 1% of the maximum possible predicted gain. Table 11.6 shows that this strategy also resulted in the largest loss in MAI, primarily as an indirect method for increasing DEN (breeding objective trait basic density). This phenomenon was also evident in the index coefficients calculated for the STBA selection criteria (Table 10.10, Chapter 10), and is a result of the large value placed on density by the enterprise model. Combined selection of growth and form traits achieved 33% of the maximum gain, translating to a *Present Value* profit (defined at plantation establishment) of $3.5M. The majority of this gain was attributed to the impact of branch index on profit. Indeed if selections were based solely on this trait, enterprise profitability would increase by 1.2% (data not shown). However of primary importance in increasing the predicted gain from selection was an assessment of basic density. An individual-tree assessment of basic density as the sole selection trait increases the prediction of enterprise profitability by 2.73%. Further, for the case of multi-trait selection, of the strategies presented in Table 11.5, efficiencies greater than 70% were only achieved when basic density was included as a selection trait and assessed on an individual tree basis.

It is interesting to note from Table 11.6, that LEN increased across all strategies investigated and that BIX and MAI decreased across all strategies. Indeed,

selections based on tracheid length was also shown to have a major effect on predicted gain. However the effect of this trait was assumed to be very similar to that of basic density, in that selection for either of these traits improves LEN and DEN as shown in Table 11.6. The effect of both of these breeding objective traits as modeled in Chapter 8 was very similar, however DEN was more prominent in changing profitability due to the secondary wood-flow effects (i.e. increasing DEN resulted in more mass of wood per plantation area and thus a cascading effect throughout the system of increased costs and incomes derived on a per hectare basis).

While assessments of wood brightness appeared to have a major effect on predicted gain, the negative relationship between this trait and basic density at both the selection level and the objective level, makes the trait a less attractive selective option. Further, the currently defined objective is aimed toward the production of high brightness newsprint and the importance of wood brightness as a selection trait has been shown to drop dramatically if production of a lower grade of newsprint is defined (Chapter 5). Nevertheless, increases in BRG (the breeding objective trait) were shown to be achieved indirectly for each selection strategy except those combining growth and form traits with an assessment of basic density.

Wood and tracheid properties are considerably more expensive to assess than growth and form traits (Table 11.4) and whilst assessment of all traits may show a very positive gain-return for assessment-dollar-spent ratio, tree breeders are generally faced with limited resources. An alternative strategy uses family-mean assessment for the expensive to assess wood and tracheid properties and individual-tree assessments for growth and form traits, and is thus considerably cheaper. However Table 11.5 shows that family-mean assessments of basic density and tracheid length (two of the most important traits in gain capture) result in substantially lower gains than would result if they were assessed on an individual-tree basis.

An assessment-cost scenario was presented involving the selection of 50 individual trees for deployment across 3000 hectares. The assessment budget was $100,000. Using Monte-Carlo simulation, 10,000 assessment strategies were generated allowing the total number of families, the number of trees assessed per family and the presence or absence of selection criteria to vary within constrained limits. It was assumed, however that all strategies would include individual-tree assessments for the growth and form selection traits investigated. It was also assumed that basic density and tracheid coarseness were assessed from the SilviScan apparatus (Evans *et al.* 1995) and as such assessments on one of these traits also provided information on the other at no extra assessment cost as they

are measured simultaneously. An assessment strategy combining individual-tree assessments for diameter (50 trees per family), branch index (50 trees per family), stem score (25 trees per family), basic density and coarseness (10 trees per family), and tracheid length (5 trees per family) was shown to maximise gain capture for the limited assessment resources. The fact that no assessment of wood brightness was included in this strategy was a conspicuous outcome.

In reality the resources available for assessment will be dependent upon the size of the deployment program, and organisations with large deployment programs may opt to spend more than $100,000 on assessment. However Figures 11.1 and 11.2 indicate that increases in predicted gain beyond an assessment budget of this magnitude are, relatively speaking, small. It is likely that radiata pine breeding programs in Australia face limits in the order of the $100,000 assessment budget assumed here.

15.4.1 Reliability of results

The most important trait for tree breeding, as based upon the currently defined enterprise was basic density. Branch index was also shown to be an important trait affecting profitability in the case of multi-trait selection strategies. The variation for basic density and genetic correlations relating basic density to LEN and BRG were shown to be most important, followed by the economic weight for DEN. The genetic parameters for basic density are reasonably well supported by previous work (Chapters 9 and 10). The economic weight for DEN was most sensitive to the value of sold newsprint, assuming a value well within the expected range in southern Australia. Also of importance was the correlation between tracheid length and BIX, which is currently unvalidated and was assumed here to be zero. This parameter needs to be confirmed.

It is noteworthy that some of the information used in the derivation of economic weights in Chapter 8 is unvalidated assumption. Sensitivity analysis of economic weight estimates identified key assumptions underlying economic weight estimates (Table 8.22). Yet in the application of economic weights to multi-trait selection options, gain from selection is, on the whole, more sensitive to variation in genetic parameters than to variation in economic weights. Whilst this conclusion is a function of the allowable range of variation for each input used in the Monte-Carlo simulation, the ranges used are not unrealistic.

15.4.2 On the economics of quality improvement

Increasing basic density, tracheid length, tracheid coarseness and wood brightness all impact on the quality of the newsprint produced. The models derived in Chapter 4 relating these traits to the costs of newsprint production set a minimum limit to a number of newsprint quality issues. There is little point in improving these issues beyond the defined minimum as the value of newsprint sold by the firm is unchanged. However, if improvements are made to such an extent that the newsprint can be sold at a higher grade (e.g. light-weight coated paper), then an increase in income will be obtained due to the higher value of the product. This would seem unlikely for a thermomechanical pulping and newsprint production system unless considerable changes are made to the system's components, requiring a significant outlay of capital.

Similarly, increasing the basic working stress of flitch might also increase the value of this product sold by the firm, i.e. producing stronger flitch might increase the income of the firm because stronger flitch is worth more. However, if all firms in this product sector increase the average basic working strength of their product, the premium paid may be reduced or disappear completely.

15.5 Biological traits not considered

One factor, identified by Borralho *et al.* (1993) as potentially having a major impact on plantation productivity was the issue of survival. Chapter 12, based on the methodology of Chambers *et al.* (1996) showed that this trait was under moderate to strong genetic control across two sites in southern Tasmania. However, survival, as a trait, can be determined by a number of factors. Nevertheless, Chapter 13 showed that its impact on the productivity per hectare is, whatever the cause, substantial. Indeed in areas of high mortality it may be more important, economically, to breed for survival ability rather than diameter, provided that the primary cause of mortality is known (Chapter 13). This may become paramount in the case that the major cause of survival ability is negatively correlated to individual tree growth (e.g. diameter).

Due to low value placed on plantation productivity for the currently defined production system (as determined by the small to moderate effect of *MAI* on enterprise profitability relative to other traits examined) however, the effect of survival may be expected to be negligible in this instance, providing that mortality is not extreme.

Other biological traits which have not been modeled include spiral-grain and microfibril-angle. Spiral-grain may influence the recovery of dry seasoned timber from rough-green-sawn (Sorensson *et al.* 1997), whilst microfibril-angle may influence internal checking and sawn-timber stiffness and strength and thus value (Walker and Butterfield 1995). Due to the lack of available relationships the enterprise defined here did not include a component which allowed changes in spiral-grain and microfibril-angle to influence the recovery of seasoned sawn timber from rough green flitch. Future work should develop such a component.

There is evidence that high lignin content may adversely affect tracheid flexibility and the longitudinal modulus of elasticity of wood tracheids (Chapter 2), thus affecting the costs of thermomechanical refining and handsheet strength parameters. The potential to include some account of lignin content in future breeding objectives is promising, provided the necessary relationships can be derived. Indeed, Wilcox (1973) has suggested that the absorption coefficient of wood shavings is a good indirect measure of the lignin content in a wood sample.

Other issues in newsprint production have also been omitted from the currently defined breeding objective which may require further attention. One such issue of vital economic importance is the printability of the newsprint sheet. This factor may well be influenced by changes in wood microstructure and rheology and thus sensitive to decisions made by tree breeders. Again, however there is virtually no available information dealing with these issues.

One final consideration is the impact of juvenile flowering (flowering precocity) on the genetic gain achieved over successive generations. The capture of genetic gain from tree improvement depends on both the gains produced per generation and the rate of generation turnover (i.e. incorporation of new genetic material into commercial planting stock). The generation interval is governed by the earliest age at which key traits can be reliably assessed and the time to reproductive maturity. Thus selections based on a trait such as flowering precocity has the potential to increase generation turnover and hence economic gain per unit of time. A major drawback from this idea, is that including flowering precocity as a selection trait will demand that less selection pressure is applied to other economically important traits in the breeding objective. Indeed, a theoretical study conducted by Goddard (1981) suggests that selection for traits which increase the rate of generation turnover may not be worthwhile unless very rapid gains can be made in these traits. Chapter 14, however shows flowering precocity to be under a high degree of genetic control in *Eucalyptus globulus* ssp. *globulus*. Other studies have also shown increasing evidence that this trait is under moderate to strong genetic control in many genera, including conifers (Gerhold, 1966; Teich and Holst, 1969;

Jeffers and Nienstaedt, 1972; Schmidtling, 1981; Eriksson and Jonsson, 1986; Chalupka and Cecich, 1997). Therefore the potential is there to indeed make rapid gains in flowering precocity over very few generations as suggested by Goddard (1981). Genetic correlations between flowering precocity and growth were more or less independent at age 4, and there was some evidence of a favourable genetic correlation with basic density (Chapter 14). Given the high value placed on basic density for the production system currently defined, this makes selections for flowering precocity as a means of reducing the generation interval an interesting alternative.

15.6 An objective for the future

It must be remembered that the production system must reflect the utilisation system 25 years into the future, and whilst predicting future utilisation on systems we see today is a solid starting point, the world may be very different by the time the (as yet unplanted) trees reach maturity. Two potential changes which may have impact on future markets for structural grade flitch and high brightness newsprint are:

- the changing nature of the forest resource; and
- the possibility of a taxation on carbon emissions.

Australian domestic sawn-timber supply has been dominated by the availability of slow-grown native forest wood, and, more recently, plantation-grown softwood. The future sawn-timber industry may face reduced native-forest sawlog supply, and plantation-wood which has been grown faster than the current plantation resource. The way in which grown wood is processed and used is largely an artifact of the availability of the raw material. As slower-growing native forest resources are depleted and replaced with intensively managed short-rotation forests the characteristics of the raw-material will change: log size, basic density, stiffness, kraft pulp yield, cell-wall thickness and fibre length may all decline. This may alter forest-product production possibilities which will eventually alter consumption patterns.

The introduction of a carbon emissions tax may increase the cost of alternatives to sawn-timber and liner-board. The carbon neutrality of forest products, and the potential opportunity cost of leaving the standing plantation as a carbon store may considerably alter the value of forest products.

15.7 Conclusions

In general, the production system defined in this thesis will provide considerable insight into the economic implications of tree improvement. It has wider application to plantation forest management to, for example, the selection of deployment sites or the selection of optimum fertiliser regimes. However further improvements are required as new insights and information become available. Indeed, the thesis touches on a number of issues as yet unresolved in the definition of breeding objectives for the forestry and forest products industry. However, the definition of a breeding objective is a continual process and reoptimisation is recommended (Goddard 1998). As described by Oliver Mayo[10] at a recent conference: "the correct definition of a breeding objective is the least worst thing we can do as breeders". At the very least, a definition of the breeding objective allows industrial tree growers and mill managers to critically examine their processes in the quest for higher quality plantation forestry.

More specifically:

- there is some evidence that the gains in newsprint strength achieved by adding increasing amounts of kraft pulp (an expensive commodity) to a TMP furnish, may not manifest until a minimum amount of kraft pulp is added (between 3 and 8%);
- the cost of thermomechanical pulping and newsprint production could be reduced by increasing basic density, mean tracheid length and wood brightness and decreasing tracheid coarseness of wood entering the TMP system;
- wood brightness and tracheid coarseness (which have a major effect of the optical properties of the final newsprint sheet) become less important as the assumed paper grade drops to lower grades of newsprint;
- a bioeconomic profit function of the form $PROFIT = f(\mathbf{g})$, where $\mathbf{g}$ is a vector of mean genetic values of the forest (one per trait) should be defined (this may also contain a vector of management controlled variables $\mathbf{m}$) which has been demonstrated to the best method in describing an objective;

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[10] Oliver Mayo, 'IUFRO '97 Genetics of Radiata Pine', Rotorua 1st-4th November 1997.

- the profit function should assume an optimised level of management that can not gain by increasing the scale of the enterprise and should be defined in terms of 'long-term profit';
- as defined here, growing cost is only 5.5% of the total costs of producing structural grade flitch and high brightness newsprint from thermomechanical pulp and therefore the value of tree improvement must be evaluated over the entire production system;
- the most appropriate method of estimating the economic value of tree improvement is *Profitability Index* calculated over the entire production system;
- basic density has a major impact on the profitability of the production system, however tracheid length and wood brightness also appeared important in this respect;
- bark volume, stem sweep, stem taper and tracheid coarseness appeared to have a low impact on production system profitability and may be ignored as a simplifying assumption, in any future efforts to improve the definition of the bioeconomic model;
- in relation to multi-trait selection options, the two most important selection traits were basic density and branch index;
- due to the negative genetic relationship between basic density and wood brightness, the attractiveness of some assessment of brightness in selection strategies is diminished;
- assessments of growth (diameter at 1.3m) at age 10 had a very negligible effect on the predicted gain in profitability;
- a 'traditional' selection strategy based on individual-tree assessments of growth and form traits captures only 33% of maximum gain, however the addition of similar assessments of basic density increases the gain capture to 78%; and
- wood properties are expensive to assess and thus individual-tree assessment of these traits may be prohibitive, however the gains to be made from individual-tree selections compared with selection based on family-means for basic density and tracheid length are significant and well worth the additional associated cost.

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